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Comfortization of Aircraft

Albert A. Arnhym
Solar Aircraft Company

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PREFACE

Every step forward in the speed of transportation has been followed by corresponding improvements in comfort. We are a comfort-loving race. One of the essentials in our daily living, it appears, is to achieve a degree of comfort to the physical senses. This tendency goes far back to the dawn of mankind where the first invention in the chilly cave was perhaps a wooden stool or possibly an arrangement of stone slabs around the fire to carry away disagreeable smoke and secure the comfortable heat.

Probably also, this early ancestor found that his luxurious smoke-free cave was desired by others and he had the choice of fighting for its possession or successfully selling his services to other Pleistocene neighbors—men who were not sufficiently skilled to build a chimney or who could not master the intricacies of a wooden stool.

Judging by the actions of descendants—a breed of men now known as "Engineers"—he fought for his rights and also successfully used his skill to the ultimate benefit of the human race. If he didn't, the ideas soon were copied and these and other creature comforts were widely disseminated and accepted.

In the field of transportation the saddle and particularly the wheel were basic inventions of enormous importance. Later the wagon gave way to the coach, the trolley to the bus and, since the turn of the century, the early attempts at a gasoline-propelled horseless carriage have resulted in the luxurious motor car of today.

Now again, within our own generation we have man's mastery of the skies. In this brief span of forty years we have seen the first successful heavier-than-air flight of a few minutes grow to speeds equal to the speed of sound. Military requirements in both Wars dictated the development of this invention toward improvements in speed and altitude. Little has been achieved toward comfort. And yet, if the aeronautical engineer or builder neglects this phase his product will not meet with public acceptance. Throughout all history, men have succeeded who invented or sold "comfort." It is my feeling this is and will be particularly true in the airplane industry.

Even here, there is a lesson to be drawn from our Neanderthal ancestor whose cave with stools and chimney is to a modern scientifically heated house as the present airplane heating system is to "X."

Or to put it another way: Has the comfortization of aircraft gone very much further than the stool and rock chimney era?

Albert A. Arnhym has reached into this new territory in the present book. It is believed that his work is a contribution to a subject the importance of which is not fully grasped.

EDMUND T. PRICE

San Diego, California.

ACKNOWLEDGMENTS

In June 1942 the *Aero Digest* published an article by the author, entitled "Comfortization of Military Aircraft." This was followed, in August of the same year, by a discussion of Air Supply, and subsequent articles dealing with Heat Supply, Soundproofing and other comfort features for military airplanes.

The suggestion to treat all of this equipment as a single accessory group and a very important one at that, met with general approval and resulted in numerous requests to the *Aero Digest* and the author for reprints and elaborations. In the light of such interest the publication of a detailed text on aircraft comfortization seems justified.

Military restrictions and the lack of organized information make it extremely difficult to compile the manifold data required to cover so broad a subject. As a consequence, it has been necessary to secure the assistance of a great many individuals and organizations, whose invaluable services should be properly acknowledged.

The completion of this book has been made possible by the generous assistance of Solar Aircraft Company. Particular appreciation is expressed to Edmund T. Price, President, who kindly consented to write the preface and whose interest and encouragement has helped so much. Other members of the Solar staff who have contributed to this book are: H. A. Campbell, Director of Research, who placed the personnel and facilities of his department at the author's disposal; G. B. Hodgson, Staff Engineer, who rendered countless services by assisting in the calculations, computation of curves and careful checking of the entire text; Paul A. Pitt, Experimental Engineer, who supplied many of the data on heat exchangers: P. L. Ferris, Advertising Manager; S. P. Weston, Staff Photographer; Miss F. Box, who drew most of the curves and sketches; and, last but not least, Connie Biernat, who bravely typed her way from one deadline to the other.

As mentioned before, the *Aero Digest* was the "godfather" for this book. In addition, it not only gave the permission to quote entire paragraphs from the above mentioned articles, but also supplied many of the cuts used in them which proved of considerable help. For this reason, it is a privilege to acknowledge the cooperation of the following gentlemen: Frank A. Tichenor, Publisher; Russel C. Johns, Assistant Publisher, now with the Army Air Forces; and James C. Galloway, West Coast Representative.

Appreciation is also expressed to the editors of the British magazine *Flight* for their permission to reprint parts of an article by D. C. Greenwood.

So many individuals have cooperated in this work that it would be impossible to name every one of them, but the following have been of particular help: Doctor Stephen Zand who, some years ago, taught the author the fundamentals of aircraft soundproofing and supplied a priceless collection of data and information for use for this manuscript; Howard Ketcham, famous stylist of airplane cabins, through whose associations the author first recognized the importance of comfortization; and T. A. Biernat, of Consolidated-Vultee Aircraft Corporation, who painted the water color of a Curtiss "Condor" shown in Fig. 1.

Among the many people who encouraged the author to undertake and continue what often appeared to be an almost hopeless task, it is desired to mention especially R. C. Gross of Airmax Corporation and Solar Aircraft Company, who has been a loyal friend and companion; Wing Commander John T. Mynors of the British Air Commission; and George A. Page, Jr., Director of Engineering for the Curtiss-Wright Corporation.

In spite of severe military restrictions and burden of work, the following companies and organizations have contributed a vast store of data, information, photographs and other material:

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The cooperation and assistance of all of the individuals and organizations named above are acknowledged with sincere gratitude.

Albert A. Arnhym

Los Angeles, California

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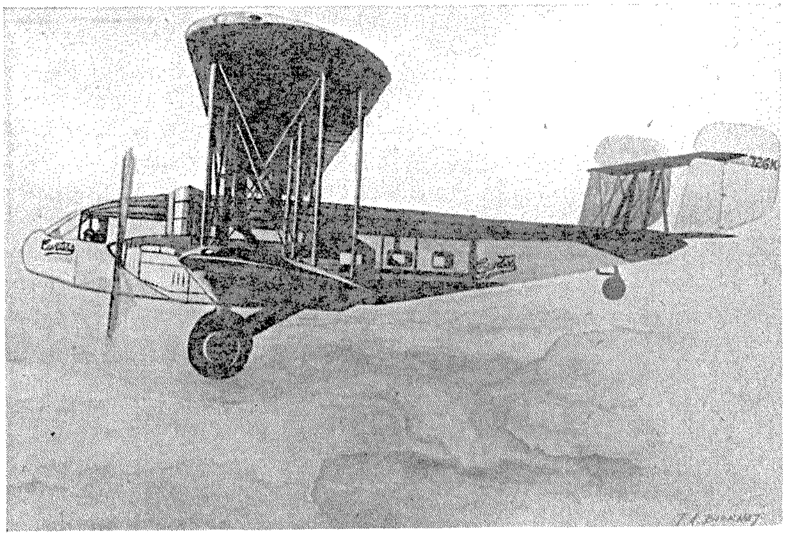
I

INTRODUCTION

Originally, there was only one requirement for an airplane, namely, that it could fly. However, once the novelty of heavier-than-air flight had worn off, the mere fact that the new contraption could rise a couple of feet and stay in the air for a few minutes did not suffice. Increasingly heavier demands were made by those who became interested in flying, resulting in rapid attainment of longer flights, greater altitudes and speeds, and a higher degree of safety.

This development is by no means completed today. Although the speeds, ceilings and ranges of modern aircraft are fantastic compared to those of only a decade ago (Fig. 1), the contingencies of modern air transport and warfare alike require further increase and improvement.



Drawn by T. A. Biernat for "Comfortization of Aircraft"

Fig. 1. The Curtiss "Condor," one of the first commercial transports to be equipped with scientific comfortization.

The ensuing problems are fundamentally the same for both civil and military aircraft. To the slide rule it makes little difference whether a required greater useful load is for the purpose of carrying more passengers, cargo or bombs. The problems of high-altitude flight remain the same, whether such altitudes must be reached for purposes of smoother and faster passenger flight or to avoid anti-aircraft fire.

Thus, instead of impeding development, requirements of military air operations have stimulated it. Once this war is over, the planes which our industries had to develop to win it will be far superior for peace-time purposes to the finest planes we had at the outbreak of the war.

These considerations apply primarily to the flying qualities of aircraft, that is, such features as permit greater ceilings, speeds, loads, range, maneuverability and safety. In concentrating on equipment necessary to attain these features one vital feature: comfort, has been sorely neglected.

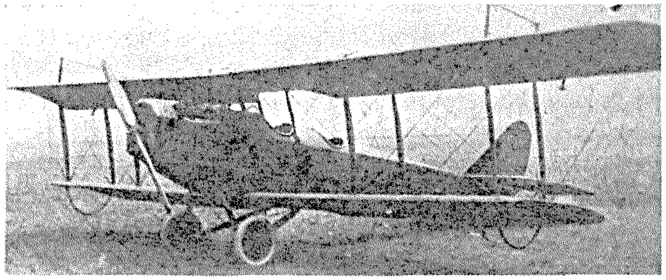


Fig. 2

Offhand, it may appear ridiculous to compare the importance of comfort with that of the basic flying qualities of an airplane. Flying is considered a most thrilling experience by many. But today, the man in business suit, at the controls of a well-heated and comfortable cabin plane, is not a flier. He is merely an altitude driver. Just as the mountain climber considers the cold and pain and effort as a necessary part of the thrill he is seeking, the thrill flier would not feel like a flier unless the ice-cold air blew into his face and the cramped cockpit made his back ache (Fig. 2).

The first airplane passengers were not better off than the pilots; it is doubtful whether they expected to be. Even when individual operators began to carry paying passengers, it did not occur to them to waste valuable pounds by putting a stove into the cabin and fixing it up with sofas and drapes, washrooms and drinking fountains just to make their fares feel at home. There were sliding window panes for ventilation, blankets against the cold and cotton to stuff into the ears. What more could anybody want, if he craved the privilege of flying as a passenger in an airplane?

This attitude changed quickly when the first airlines were organized, and the problems of promotion and competition became apparent in the balance sheets of the new industry. Stephen Zand tells of a prominent executive in the aircraft industry who, during a meeting of airline operators, told of a transcontinental trip from Los Angeles to New York in 1931 which lasted about thirty hours (extremely fast for those days) yet he complained that, for 48 hours afterwards, he was unable to work so that he had gained little time over a train (Fig. 3).

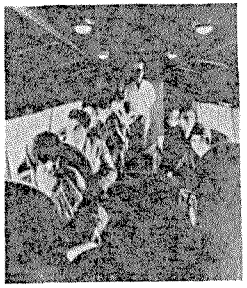


Fig. 3

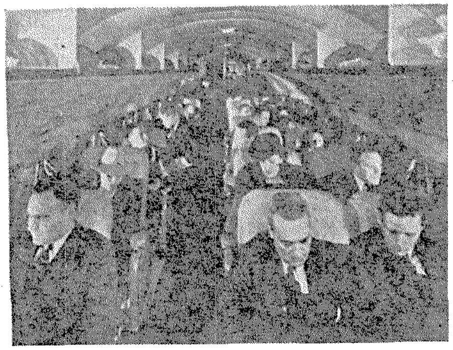


Fig. 4

The men who attended this meeting agreed that commercial air traffic, in order to appeal to wider circles and to prosper, had to consider the comfort of paying passengers, even at the expense of valuable weight. Zand was commissioned to investigate the question as to what passengers considered most objectionable in air travel and the means to overcome these objections. This was the beginning of planned aircraft comfortization.

The airlines began to look around for suitable heating equipment, for comfortable seats and, later, berths. They installed lavatories and included galleys to provide full-course meals. They had their planes soundproofed and retained men like Howard Ketcham to design artistic interiors. Every new type of commercial transport aircraft was more luxurious and comfortable than the previous one, yet little of the comfortizing equipment developed so far has found universal approval and acceptance (Fig. 4).

The reasons for this are obvious. The rapid growth of aircraft created an entire new industry which, as wide-spread as it had to be, was an entity in itself. The people who built the air-frames, the engines, the instruments and other flight accessories, had a clear understanding of the problems involved and they solved them together before the planes came off the drawing boards. On the other hand, the factories and even stores which had to furnish the seats and the galleys, the heaters and the appointments came in when the plane design was all but completed. Although they knew little or nothing of the conditions existing during flight at great speeds and high altitudes, they simply provided whatever they thought to be the lightest and most efficient. It was difficult to convince them that equipment which works perfectly on the ground will not, of necessity, work in a plane flying at 200 miles an hour and an altitude of 20,000 feet, or that a relay which has successfully withstood every test on the ground may not operate satisfactorily at low humidities and in thin air and may fail in the first steep bank when unexpected centrifugal forces play their tricks.

This was particularly true for comfort accessories because it did not pay to initiate costly development work for the small quantities and returns involved. As a result, each airline had to leave it to the aircraft manufacturer to comfortize his plane as close to the specifications as possible. The manufacturer, in turn, had to obtain this equipment and the men to design and select it wherever he could. Accordingly, the specifications differed as much as the equipment, and even the most fundamental requirements and principles involved remained the subject of half-hearted discussions and individual decisions. Thus, the installation of comfortizing equipment became so complicated and expensive that it was almost entirely reserved for commercial passenger liners where price and even weight of tailor-made equipment was less important than the wishes of the customers.

Nevertheless, passenger comfort had to be obtained at the utmost saving of weight as it was considered necessary only in order to attract enough customers to make the plane or line pay. This became particularly apparent in providing comfort for the crews of commercial airliners. While crew members were furnished such equipment as was considered essential for efficient discharge of their duties, most of the conventional means for comfort were not adjudged to fall into this class.

As recently as four years ago the author saw specifications for an airliner which provided every reasonable comfort for the passengers while the instructions for ventilating the flight-deck read about as follows: "If ventilation is desired for the flight-deck, the windshields are to be opened slightly." Granting that men have been and are still flying under worse conditions than that, a pilot operating in a badly ventilated or ice-cold cabin cannot be as efficient as a person in charge of the lives of some dozen people has to be. There is no need to go into the details of what may happen, if any member of the crew, from the captain to the stewardess, should be handicapped by fatigue or other physical effects due to lack of comfortization.

Fortunately, designers and operators of commercial transports soon realized that the loss in weight caused by comfortizing equipment for the crew, actually brings a more important gain, namely, that of increased efficiency, vigilance and physical fitness. The modern airline executive will, therefore, give the crews of his planes all such aids which contribute to their physical comfort and thus decrease the danger of accidents caused or aggravated by human failures (Fig. 5).

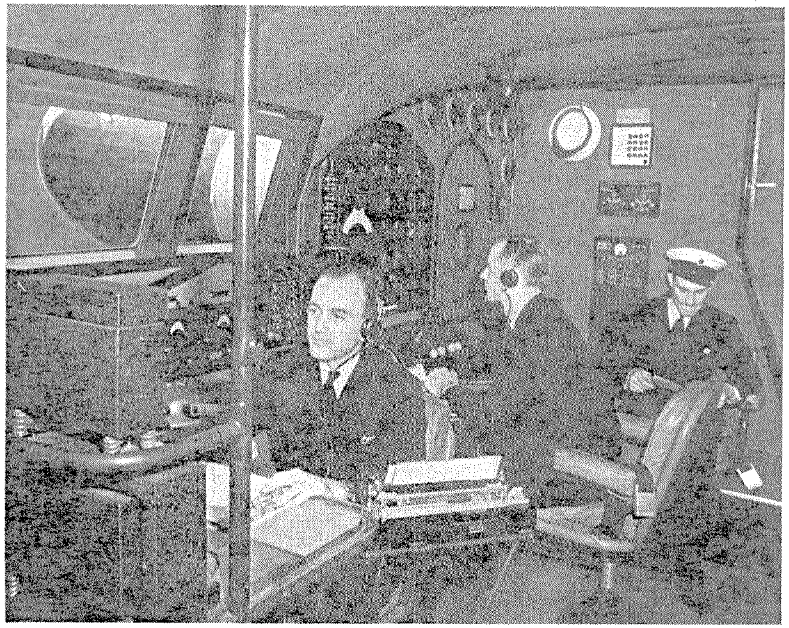


Fig. 5

The same considerations hold true in deciding what measure of comfort should be furnished to the crews of military aircraft. To start with, it seems ridiculous to even mention the need of comfort for healthy, young soldiers. Would anybody dream of suggesting umbrellas for soldiers on guard so they won't catch cold, if they are on duty on a rainy night in No Man's Land? A soldier is willing to sacrifice his life, and he may be called upon to do so from one hour to the next. Sore feet, an aching back or a running nose are of little significance, if the very life is at stake.

Apparently, this applies to an even greater extent to the pilot of a military plane. A flier in combat or on a bombing mission over enemy territory is in a situation where a headache or a sniffle are so insignificant compared to his chances of losing his life or serious injury, that it seems a crime to sacrifice a bomb or a belt of ammunition in order to take a heater along. Offhand, this sounds very reasonable.

There is, however, another way of looking at it. Soldiers in the Arctic are furnished heavy, protective clothing although it impedes their movements and interferes with their functions. Since the lack of such clothing would seriously affect their efficiency and health, and might make them entirely worthless or even a burden to their comrades, comfort, in this case, is more important than the loss in agility which it entails, and becomes a military necessity. In providing comfort equipment for military flight crews the engineer must be guided by similar considerations.

The part of the engineer in times of war is twofold: he must create weapons superior to those of the enemy and protection against such weapons in the enemy's hands. Thus, while the engineer neither fights nor plans a war, its outcome may very well depend on his ability to outsmart the engineer on the other side. Since the present war is dominated by the airplane, the engineer has to use all of his scientific training and experience to constantly improve this particular type of weapon over that produced by the enemy, and this with the same determination and ingenuity with which he has learned to improve on the product of a bitter competitor. In other words, he must approach every one of his problems solely from the standpoint of good engineering, no matter whether the end-product has to serve commercial or military purposes.

One of the fundamental considerations in engineering a commercial product is the convenience and comfort of the user. The belief that such consideration is unnecessary in the design of military implements is erroneous and, particularly so, in the case of military aircraft. Recent events on the fighting airfronts all over the world have shown convincingly that military flight crews deserve as much or even more consideration as the user of a commercial product, and that the provision of a certain amount of comfort is not less important than the design of the airplane itself.

The crew of a bomber, for instance, is in full charge of a highly valuable piece of equipment. It is not the cost in dollars which makes this equipment so valuable. It is the time, the facilities, the men and the badly needed material it takes to build and equip it. They are not flying this bomber for the sake of income or entertainment. They are guiding an extremely important weapon for defensive or offensive action. If they are operating this weapon successfully, they and their bomber can attain more than a whole regiment of infantry, a battleship or a battery of guns. If they are unsuccessful, it means not only loss of a bomber and its crew whom it took many months to train, but also possibly loss of an opportunity to prevent damaging hostile action (Fig. 6).

The fact that one warplane is successful while another one of the same type with the same armament and a crew of the same training is not, can be explained primarily by one fact: the crew of the former was in better shape. "Luck is the accident that happens to the competent," and the skill, proficiency and physical fitness of the individual flier or a flying crew as a whole must be the deciding factor during action in the air, if all other odds are even.

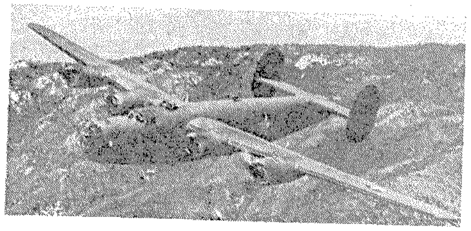


Fig. 6

Thus it becomes obvious that comfortization of military aircraft is as vital as offensive equipment itself. To decrease the bomb-carrying capacity of a plane by a few pounds in order to provide heat for its pilot is less consequential than if the plane is shot down before it could even drop its bombs just because the frozen fingers of the pilot could not handle the stick as well as his enemy. To decrease the speed of a bomber by a few miles in order to install soundproofing is less important than to lose the whole ship somewhere over the ocean because the drumming ears of the pilot were unable to hear the radio signals to guide him home.

Any member of a bomber crew who has been exposed to cold, lack of proper ventilation, hammering noise and no real rest for 15 hours or more is in no position to man the battle stations when, on the way home, enemy aircraft attacks. Oxygen is provided for flying at high altitudes because the men would die for lack of it. If they lack the other essential necessities of comfort, they don't die from exposure or exhaustion, to be sure, but they die because they are unable to defend themselves against an enemy who is out to kill them. Thus, in comfortizing a military plane, it is not only the pilot or the crew who profit by it but the airplane itself which becomes a more powerful and efficient weapon since its human control mechanism is operating at a greater efficiency.

II

THE COMFORT ACCESSORY GROUP

1.0 General Requirements

An airplane consists, essentially, of *airframe, engines* and *accessories.* The accessories, in turn, may be divided into those pertaining to *flight, commercial* or *military,* and *comfort.*

In comparing the relative importance of these accessory groups it is erroneous to assume that the one or the other should be given preference in the distribution of weights and space. The need for flight accessories, such as instruments, gyropilot, controls, hydraulic system, supercharger, etc., is self-evident. This is equally true for commercial accessories, that is, provisions for carrying passengers or cargo, or for military accessories such as guns, munitions, bomb sights, and similar equipment.

The importance of the third accessory group, that of comfort, is not always fully admitted nor understood. It is argued that, up to a few years ago, both flight crews and passengers had to be contented with little or no comfort equipment at all and got along very well. The fallacy of this assumption has been pointed out in the previous chapter, and it has been shown that comfortization is as important for passengers as for the flight crews of commercial and military airplanes. Then the question arises as to what measure and type of comfort is required. Obviously, the extent of comfortization is determined, on one hand, by limitations of weight, space, electric current consumption and service considerations and, on the other hand, by the minimum physical requirements of comfort.

Briefly, *comfortization can be defined as the art of minimizing or eliminating the discomforts inherent to flying.* This definition is vague enough to allow the widest interpretations. The differences in opinion as to what constitutes comfort in general and essential comfort in particular, apply equally to commercial as to military aircraft. By the same token, the definition of essential comfort in itself must, of necessity, be based on factors which are again entirely different.

In one case, comfort is provided to give a paying passenger the benefit of complete relaxation and rest while traveling. If these conditions are not met, he will use planes of another airline or travel on the ground whenever possible. Thus, comfort on the commercial airliner is an accommodation necessary in the interest of profitable business operation. Indirectly, this is also true in providing comfort for commercial flight crews.

Comfortization of military planes is based on another type of balance sheet, that of striking power *vs.* weight. The crews of such planes are working hard most of the time and are under a terrific mental and emotional strain. They cannot cancel their reservations and if they fail, no matter for what reason, the consequences to themselves and to a multitude of other people may be dreadful. Therefore, the scope of comfortization of military planes is much narrower and more clearly defined.

Obviously, the extent of essential military comfort will vary considerably for different planes, different purposes and even different fliers. While some persons, for instance, are wholly unaffected by noise of certain frequencies, others actually suffer physically and become unfit for their task. One solution of this problem would be to eliminate all such men from flight duty although others, less sensitive to noise, may be much more sensitive to cold, heat or high altitude.

However, it is impossible to eliminate everyone who is affected by the one or the other discomfort of flying. It is much easier to eliminate such discomforts as are common sources of serious handicaps and thus ease the restrictions which are still keeping many otherwise qualified young men out of the air.

To arrive at an understanding of what constitutes essential airplane comfort, it is, therefore, best to define it for commercial aircraft first and then narrow it down to the specific requirements of aerial warfare.

2.0 REQUIREMENTS OF PASSENGER COMFORT

Stephen Zand, after completing the investigation mentioned in Chapter I, listed the following objectionable discomforts, enumerated in the order of their importance:[1]

1. Noise;
2. Ventilation;
3. Changes of the attitude of the airplane (bumpiness);
4. Heat or cold;
5. Improper seating accommodations producing muscular fatigue;
6. Mechanical vibration;
7. Rate of climb or descent;
8. Altitude;
9. Smell.

Immediately after completion of this list steps were taken in co-operation with both aircraft manufacturers and airlines to eliminate the major discomforts. One of the results of these efforts was the design of the 18 passenger Curtiss "Condor" by George A. Page, now Director of Engineering for the Curtiss-Wright Corporation, who, together with Zand, incorporated in this plane what was then the first scientific soundproofing as well as heating and ventilating installation on a passenger airplane (Fig. 7).

Fig. 7

Only a few years later W. W. Davies of United Airlines revised the above list considerably, proving that some progress had been made, both in the development of comfortization equipment and in the realization of the scope and necessity of comfort. He divided passenger comfort into two groups: *indirectly* and *directly* contributing to comfort.[2]

Directly contributing:

1. Space accommodations;
2. Interior design;
3. Noise prevention;
4. Heating and ventilating;
5. Lighting;
6. Catering.

Indirectly contributing:

1. Oxygen equipment;
2. Lavatory facilities;
3. Sanitation and fumigation;
4. Airplane operation;
5. Vibration.

The interesting difference between the lists of Zand and Davies is the addition of factors which show a marked tendency toward providing not only physical but also mental and emotional comfort as evinced by the emphasis on interior design, lighting and catering. Both stress the importance of heating, ventilating and prevention of noise and vibration.

A third and final list takes into account the latest developments and specifications of both airline operators and manufacturers as well as the more clearly defined trend in providing passenger comfort. This list reflects the advance in serious desire to make air travel comfortable and enjoyable, even at the expense of considerable weight:

1. Air conditioning;
2. Noise and vibration control;
3. Seating and berthing;
4. Comfort of air travel;
5. Lavatory facilities;
6. Lighting;
7. Styling;
8. Catering;
9. Ease of motion;
10. Entertainment.

Each of these items is as important as the others in creating complete comfort and attracting paying passengers. However, while all of these items should be given equal consideration and effort, lack or deficiencies of those higher up in the list will cause serious discomfort and even physical pain while the others are desirable only from a standpoint of complete relaxation and traveling enjoyment, comparable to that on luxurious trains or boats. Surprisingly enough, only few of these items can be omitted in a similar list of essential comfort on military aircraft.

3.0 Requirements of Military Comfort

3.1 AIR CONDITIONING heads the commercial list. There is no doubt that the supply of air and heat is equally vital on military aircraft. However, while heating and ventilating on passenger planes are usually furnished by the same equipment, military requirements often necessitate a strict separation of these two items. In this separation the top position goes to ventilating which, in this case, is more appropriately termed "Air Supply." This item includes not only the normal supply of fresh air to the cabin or individual stations but also the supply of oxygen at high altitudes, cabin supercharging, blasts of cold air to prevent black-outs, etc.

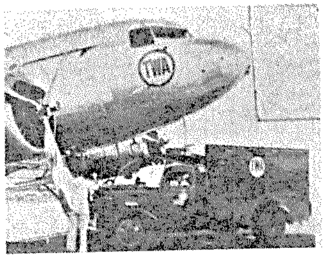


Fig. 8

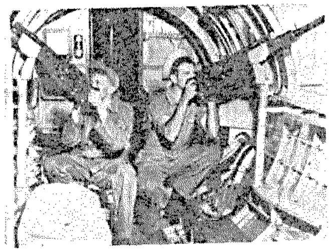


Fig. 9

Heating, the second requirement for essential comfort on military aircraft, comprises all equipment and devices for the generation and distribution of heat; heating of cabins or individuals, anti-icing and prevention of fogging of windshields, or for the heating of military equipment and apparatus such as cameras, gun breeches and the like.

No provisions are made for cooling and humidity control. However, even the most modern airliners lack this comfort, simply because there is no equipment available, as yet, which will provide efficient, complete air conditioning in the air. While attempts have been and are being made to utilize the vapor in the exhaust gas for humidification at high altitudes, it is *excess* humidity which must be dealt with on military planes.

There is general agreement that cooling is not required during flight as long as individual cold-air nozzles are provided which supply outside air to passengers as desired. Actual refrigeration is considered necessary only for an occupied plane on the ground. Commercial airlines solve this problem by using elaborate ground equipment for air conditioning of planes before occupancy or during long stopovers (Fig. 8). Obviously, such equipment is out of the question for military purposes.

3.2 NOISE AND VIBRATION CONTROL are usually interdependent on commercial planes. On military aircraft these items must again be separated. Vibration control is employed only where its lack would affect the operation and life of equipment used for flying or military purposes. But control of excessive noise must be undertaken even at the cost of valuable weight.

It has been established definitely that the high noise levels encountered in most airplanes cause hearing losses in pilots, although not always to the same degree. Continued exposure results in decreased acuity for tones of lower pitch. The affected pilots must turn their radios on louder and louder to hear the radio guide beam at low frequencies or for certain words, and even this will become ineffective. Pilots grow unable to hear landing instructions with the required exactness or, for that matter, other vital messages which must be received complete in order to be understood. Noise is a serious enemy and must be dealt with properly.[3]

3.3 PROPER SEATING and BERTHING come next on the comfort list for commercial airliners. Again, there must be a distinction between comfort for paying passengers and that for soldiers who are at work and must be kept in fighting trim. A seat on an airliner should be so designed as to give the passenger the complete comfort of relaxed rest, and, it is often required to convert this seat into a comfortable berth with a minimum of effort, time and added weight.

On the military plane, it is of the utmost importance that every crew member can remain at his respective station for any length of time with a minimum of physical discomfort. A pilot, cramped into a hard and uncomfortable seat, can certainly not be expected to react as freely and quickly as if his body were rested. A radio operator, his body aching from balancing on a hard stool for hours at a time, cannot concentrate on his vital duties. The gunners and bombardiers are usually even worse off although their duties require at least as much physical effort and fitness as those of the others (Fig. 9).

During long-range reconnaissance or bombing missions the matter of rest is as vital as the supply of air or food. However, rest is absolutely useless and possibly even harmful, if it does not provide complete relaxation. Proper seating and resting facilities are, therefore, the next requirement for comfort on military aircraft.

3.4 COMFORT OF AIR TRAVEL is the next item on the list for airliners. This refers to overcoming or minimizing such discomforts as are common for air travel: air-sickness, the effects of altitude and of sudden changes of the attitude of the airplane, quick ascents and descents, ear trouble, etc. Commercial airlines have, so far, not been able to do very much about these discomforts but they are trying to decrease their effects on the average passenger. Skillful piloting can do much to allay them within certain limits. This, however, is impossible in aerial warfare. It would be ridiculous and even criminal for a military pilot to gain or lose altitude in accordance with comfort instead of the requirements of the moment.

In selecting the personnel of fighting aircraft one of the primary conditions is that the applicant is unaffected by the discomforts of air-travel itself; there is nothing that can be recommended to counteract these discomforts that would not, at the same time, seriously affect the fighting qualities of both aircraft and crew. For this reason comfortization of air travel has no place on military aircraft.

There is a different kind of comfort which must be added instead. While the movements of military planes are, of necessity, often extremely abrupt and require very fast ascents and descents, they usually will not handicap the average flier. Unfortunately, this does not apply to the pilot and gunner of a dive-bomber. It goes without saying that the tremendous speeds and gravitational forces encountered in dive-bombing and, particularly, in pulling out of a dive are more than even the healthiest human body can stand for long.

Medical and technical research in "black-outs" of dive-bombing pilots has gone a long way in examining the causes and finding means to prevent them. Although the conditions under which dive-bombing is undertaken are so different from most other war aircraft, prevention of black-outs and similar effects of dive-bombing offers a phase of comfortization which is as strange to the commercial airliner as comfortization of air travel is to the military airplane: "Fighting Comfort" should rank next in the list.

This includes means for prevention of black-outs; seat armor and other protection against shell splinters; suitable flight gear and accessories; first-aid equipment; parachutes; life rafts and such other

facilities as will assist the fliers in overcoming the effects or after-effects of aerial combat.

3.5 LAVATORY FACILITIES are another requirement on the commercial list. Space and weight limit such facilities but certainly they cannot be primitive. A businessman who travels to save time, wants to wash and shave before stepping off the plane. For this reason, hot and cold running water, electric outlets for razors, etc., are provided for his comfort.

The men on a bomber can live and fight with or without a beard, and their physical comfort will not be seriously affected if they cannot wash their hands for the duration of a flight. However, there should be suitable toilet facilities on long-range warplanes if only for the exigencies of sanitation and health.

3.6 PROPER ILLUMINATION is of far greater importance on the military plane than on the commercial craft. The general lighting of the cabin of an airliner is usually synchronized with the styling of the plane. It is soothing, cozy and, therefore, often insufficient for activities requiring good light. However, the only activity of this type which the average passenger performs is reading, and for that purpose reading lights are provided. Limitations of weight and current are always in evidence, even where more light is desirable, such as in the lavatories, but usually not to such a degree as to affect the comfort of the passengers.

However, in all fairness to the designers of the interiors of military aircraft, it seems that the problem of proper lighting and illumination has not been given the importance it deserves. It is not enough that maps and dials, levers and switches, markings and calibrations can barely be found and distinguished. They must be so readable as to make errors impossible. This necessitates well-designed illumination which should avoid glare, reflection, leaks to the outside or interference with the work of other crew members. Improper lighting will result in eye fatigue, headaches and general impairing of the physical well-being of the men whose eyes are over-taxed. If the comfortization of warplanes is accepted as an essential and integral phase of the design of such craft, lighting must and can be added to the list of required comforts.

3.7 STYLING of the interiors of air liners has become an important phase of cabin design. Artistic selection of colors, fabrics and appointments give the passenger an added feeling of comfort, of spaciousness and relaxation. However, styling is a comfort of choice rather than necessity and is an important item on the list of commercial requirements merely because it greatly aids in attracting passengers. While it would not require added weight, space and cost to design the interior of a military plane with taste and appeal, it would be going too far to class such a feature as military comfort. The manufacturers of military aircraft will use their own judgment in properly designing interiors of warplanes (Fig. 10).

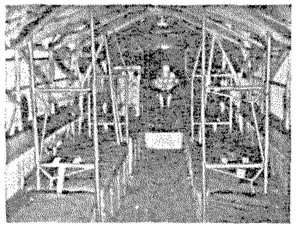


Fig. 10

3.8 CATERING should not be a surprise item on the suggested list for comfort on military craft. A flier whose mental and physical reserves are constantly drained during a flight under wartime conditions must be fed properly in order to remain in full possession of his fighting qualities. The provision of properly selected and warm food and means for keeping it appetizing and fresh, as well as a supply of suitable drinking water, are essential for comfort on military aircraft.

3.9 EASE OF MOTION ranks next on the commercial list. This requirement permits passengers' movement in, out of and into seats and berths, or through the plane and into other compartments, lavatories, etc., without unreasonable difficulty. Space limitation is the prime factor which makes it difficult to find a satisfactory compromise. However, close co-operation between the designers of the plane interior and those of the seats, berths and fittings will usually result in acceptable solutions.

On military aircraft quick and unimpeded motion from one part of the plane to the other, or from and into a station becomes vital. Such rapid movements are often of the utmost importance. Ease of motion becomes an even more important requirement of military than commercial plane comfort.

3.10 ENTERTAINMENT closes the list of comfort for air passengers. Like styling, entertainment is a sales requirement for the airlines, and a comfort well appreciated by passengers. Magazines, windows suitable for viewing the scenery and flight routing designed to fly over interesting territory are some of the entertainment features.

The crews of military planes must be on the alert during every waking minute. They neither expect nor desire comfort that is unreasonable and not helpful to their task. Whatever time there is on a warplane for relaxation will be used by the men in their own way, and without any facilities.

3.11 SUMMARIZING the comforts required for the physical fitness of crews on military aircraft, the following list can be established:

1. Air supply;
2. Heating;
3. Fighting comfort;
4. Seating and resting;
5. Soundproofing;
6. Lighting;
7. Food;
8. Lavatory facilities;
9. Ease of motion.

While the order in which these comforts are listed is based on their importance, it is a matter of opinion whether the one or another classification should be shifted. However, it will be shown that there are other considerations which support this specific classification.

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[1] Stephen J. Zand, "Comfort in Air Travel," *Journal of the Royal Aeronautical Society*, July 1936.

[2] W. W. Davies, "Heating and Ventilating Up in the Air," *Heating, Piping and Air Conditioning*, January, 1941.

[3] C. C. Bunch, "The Problem of Deafness in Aviators," *War Medicine*, November 1941.

III

SELECTION OF COMFORT FEATURES

1.0 Introduction

The list of essential comfort equipment for military aircraft does not imply that all of the items must be incorporated on every military airplane. A single-seater fighter can hardly be provided with a soundproofing installation or a lavatory; a four-motored transport needs no provisions to prevent blackouts during dive-bombing attacks. In other words, a number of factors must be considered before selecting comfort features from the foregoing list. It will be found that planes of similar size have similar comfort requirements while planes of similar classification use similar means for meeting these requirements.

Although this similarity does not, of necessity, apply to the equipment selected for these purposes, it assists in establishing the limits and scope of comfort features for both military and commercial airplanes as will be shown.

2.0 Comfort Selection by Airplane Size

In selecting comfort equipment in accordance with size there are, basically, three comfortization types of aircraft:

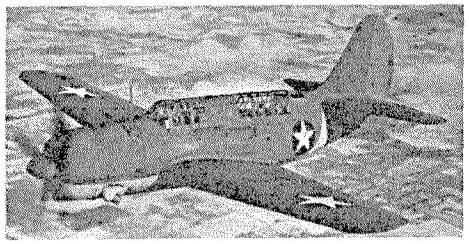


Fig. 11

1. The "cockpit" plane is usually a single- or two-seater, powered by a single engine, with full-open cockpit or a sliding cockpit hood, and very little room. Civilian planes of this type are light, private planes. Military cockpit planes are represented by fighters, interceptors, pursuits, dive-bombers, torpedo planes and trainers (Fig. 11).

2. The "cabin" plane carries a crew of three or more, is powered by one or two engines, has a closed cabin and is more spacious, permitting movement of the occupants. Its range is usually limited. To this class belong the light and medium bombers, and small military or commercial transports (Fig. 12).

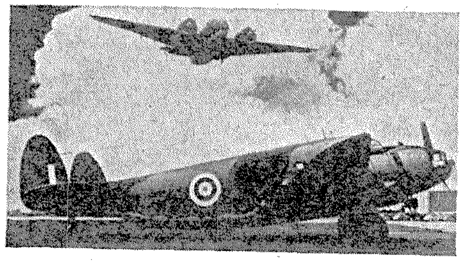


Fig. 12

3. The "compartment" plane, in addition to a crew of five or more, is suitable for carrying heavy loads such as bombs, cargo or passengers. It is powered by two or four engines, has a closed and, usually, insulated cabin. It is quite spacious, permitting the incorporation of much accessory equipment. Its range is normally very long. This is the class of the heavy bombers and large utility planes such as cargo and transport ships. The commercial version is the trans-continental or trans-oceanic airliner and heavy cargo carrier (Fig. 13).

It is obvious that all military planes, no matter what size or classification, require air supply, heat supply and fighting comfort. Seating and resting, soundproofing, and lighting, should be added for planes of the cabin and compartment types. The final three items, food, lavatory facilities and ease of motion, are normally found only on compartment planes.

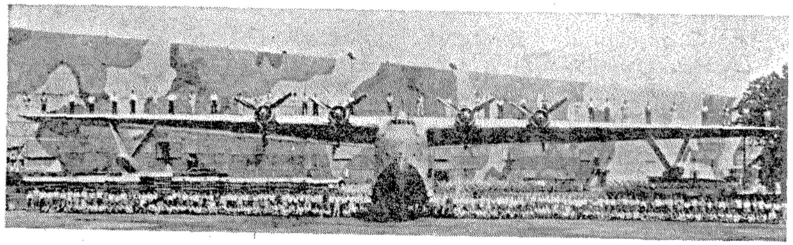


Fig. 13

Since each of the three comfort groups is typical for a particular comfortization type of airplane, it is logical to designate the first group, consisting of the first three items, as: "cockpit comfort"; the second group: "cabin comfort;" and, the third one: "compartment comfort."

In non-military planes these comfort groups consist of somewhat different features. The private plane comparable to the military cockpit plane is hardly in existence any more and will probably completely disappear after the war. The private flier will demand at least as much comfort on his plane as he can find in his automobile. The open-cock-

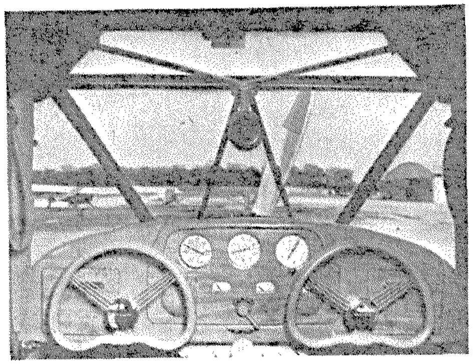


Fig. 14

pit type plane will be outmoded, used only for training or thrill flying.

Comfort requirements for such planes are negligible. Thus there will be only two general types of non-military aircraft, as far as comfortization is concerned: commercial planes and private planes.

All of the features enumerated in the list of commercial comfort equipment earlier should be mandatory for the commercial airliner of the future. Naturally, the extent of comfortization will increase or decrease with the size and range of the transport.

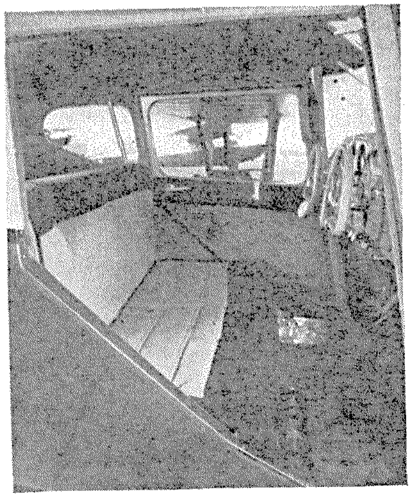


Fig. 15

As to post-war private planes, there should be the following comfort features: (1) Ventilating; (2) Noise and Vibration control; (3) Heating; (4) Comfort of air-travel; (5) Styling. These requirements are not exaggerated. The Piper Aircraft Corporation provides heating equipment and was the first to adapt a muffler to the light airplane; it is standard equipment on all their models.

The Taylorcraft Deluxe, two-place monoplane—Figs. 14 and 15—features comfort which is comparable to that of a luxurious automobile.

A summary of all comfortization types of airplanes and their requirements can be best shown in the following table:

COMFORTIZATION TYPES AND THEIR REQUIREMENTS

Comfortization Type	Comfortization Requirements		
		Military	*Non-Military*
Cockpit Type	Cockpit Comfort	Air Supply Heat Supply Fighting Comfort	
Cabin Type		Air Supply Heat Supply Fighting Comfort	Ventilating Noise and Vibration Control Seating Comfort of Air Travel Styling
	Cabin Comfort	Seating and Resting Soundproofing Lighting	
Compartment Type		Air Supply Heat Supply Fighting Comfort Seating and Resting Soundproofing Lighting	Air Conditioning Noise and Vibration Control Seating and Berthing Comfort of Air Travel Lavatory Facilities Lighting Styling Catering Ease of Motion Entertainment
	Compartment Comfort	Food Lavatory Facilities Ease of Motion	

This table is, of course, only a general guide in the selection of comfort features to assist in establishing only the minimum comfort requirements for planes of a certain size.

3.0 Comfort Selection by Airplane Classification

Although planes of the same size will, in most cases, require the same comfort features, entirely different means might have to be used to incorporate such features. The choice of these means is dictated by the scope of optimum comfort.

The scope, in turn, of each comfort item, be it air supply or lavatory facilities, depends on the characteristics of the individual plane. These characteristics fall, generally, into two classes, namely those pertaining to performance and those established by the purpose of the airplane.

3.1 Consideration of Performance Characteristics: As will be shown, air supply can be furnished in a number of ways, ranging from a simple air scoop to an elaborate super-charging system. Obviously, the prime factor in selecting the means for air supply on an airplane is the altitude at which it will normally travel. The service ceiling of a plane has also a decisive bearing on the choice of the heating system and other comfort items. Thus, *altitude* or *service ceiling* becomes the first performance characteristic which must be taken into account.

A factor of similar influence is the *range* for which the airplane is designed. If the range is very long, resting accommodations, lavatory facilities and food supply, to mention only a few items, must be more elaborate than on a plane of short range.

The *speed* of the airplane is another performance characteristic of importance inasmuch as it may decide the design of the ventilating and, possibly, heating or sound-proofing installation, as well as of such items as fighting comfort or comfort of air travel.

Primary among other major considerations of performance characteristics is the *weight* which can be allotted to the comfort equipment. Weight limitations, particularly if made unwisely, may not only seriously aggravate the design difficulties of comfort devices, but often result in the selection of wholly inadequate equipment. This applies equally to limitations of space, electric current consumption, etc.

3.2 CONSIDERATION OF PURPOSE CHARACTERISTICS: In selecting comfort equipment for an airplane, the analysis of the comfortization type, that is, the size of the airplane, will establish the comfortization group or individual features which should be incorporated. A study of the performance characteristics will usually show what type of equipment has to be used for this purpose. The final consideration of the *purpose* characteristics, will assist in narrowing the requirements to a point where adequate specifications can be written.

First among these latter characteristics is the *purpose* for which the plane is to be used. In dealing with a military cabin type, for instance, the plane may be a small transport, a cargo plane, a bomber, or a combination bomber-attack ship. Obviously, the comfortization equipment will have to be selected accordingly.

Another consideration is that of the *type and number of crew or passengers* who may have to be carried. The passengers may be paratroops who require less comfort than wounded or refugees who are being evacuated by air. If the transport is a commercial one, the extent of the comfort equipment is, of course, considerably broader.

The *climate and weather* in which the airplane will have to operate has likewise a definite influence on the selection of the comfort equipment. Some planes operate in warm and moist climates, others in very cold regions. Finally, there are planes which have to fly in every conceivable type of weather and climate and must be designed accordingly.

Particularly during times of war the question of *service and supply* becomes quite a problem. Comfort equipment requiring supplies which are not normally stored at emergency landing fields is not suitable for incorporation into a military airplane. By the same token, the service life of most military implements can be very much shorter than that of similar devices used on commercial airplanes. Equipment for flying boats must often be handled differently from identical equipment on land planes. Thus, the problem of servicing, supply, replacement, etc., may often prevent the use of certain equipment although it may meet all other requirements.

There are numerous other factors which, in some way or another, have a bearing on the selection of comfort equipment. It would be difficult to establish rigid rules as to how to cope with all of these contingencies. However, once the type and scope of a comfort feature has been established by the analysis described above, it can be left to the ingenuity of the comfortization engineer to incorporate it properly into his particular airplane.

IV

PLANNING OF COMFORTIZATION

1.0 Introduction

An automobile, no matter how powerful, becomes a worthless piece of machinery, if such minor parts as its spark plugs are removed. By the same token, an airplane depends upon all of its accessories in order to function properly.

If aircraft accessories are defined as those components of an airplane which enable the engines to make the airframe fly and keep it aloft, it is only fair to consider the flight crew as the most important accessory of all. For this reason full consideration must be given to its efficient functioning.

In comfortizing commercial airplanes it is recognized that the operation of an airplane would not be profitable unless its full carrying capacity is regularly utilized. Because improvement of comfort is one of the prime reasons for the growth of air travel, commercial comfortization is based on the attraction of a sufficient number of paying customers (Fig. 16).

Fig. 16

Thus it might appear that comfortization is serving entirely different purposes on military and commercial airplanes. Fundamentally, however, the reason for comfortizing an airplane is always the same: To operate it at greater efficiency. It is important to bear this fact in mind during the entire process of planning comfortization.

This process consists of the following steps: First, planning of requirements; second, planning of specifications; third, planning of equipment.

2.0 Planning of Requirements

The planning of requirements is usually done by the procuring agency. This may be an airline, or a military agency such as the Army, Navy and Air Forces of the Allied Nations. In the case of private airplanes the manufacturer himself can be considered as the procuring agency inasmuch as he establishes such specifications as he feels are necessary to produce a saleable product.

Ordinarily, the procuring agency will not consult the manufacturer as to the fundamental requirements of the airplane which it desires to procure. Rather, it will contact a number of manufacturers and submit to them very definite data, although it might approach a manufacturer concerning a plane which he has in production and discuss with him such changes as would be necessary to meet its particular requirements.

These requirements are not necessarily limited to size, speed, range, ceiling and similar factors but may also pertain to the incorporation of specific devices and equipment. In dealing with government agencies such a procedure often leads to the installation of what is commonly termed "government furnished equipment" and may apply to any one of the components of the airplane, from engines to machine guns.

The comfort equipment is usually not part of the requirements because its selection is actually a result of these requirements once they have been firmly established. For instance, if a plane is to have a service ceiling of 35,000 feet but should not be super-charged, oxygen equipment must be supplied. Similarly, there is no need to make provisions for parachutes and their storage part of the fundamental requirements.

Therefore, the planning of requirements should merely concern the purpose of the airplane, whether it has to serve the trans-Atlantic transport of paying passengers or dive-bombing. Since this phase of planning is based entirely on either commercial or military considerations, it should not be undertaken by the engineers but by either the airline executives or the military heads of the governmental procuring agency.

3.0 Planning of Specifications

Upon establishing the requirements of an airplane the procuring agency issues details of these requirements in the form of definite specifications for the manufacturer. The manufacturer, in turn, may request modification of such specifications if, in the opinion of his engineers, they are too difficult or impossible to meet.

Once agreement has been reached on the general specifications, the airplane manufacturer draws up considerably more detailed specifications for his own production as well as the suppliers of accessories and equipment. These, too, may request changes which can have such a bearing on the original specifications that three-sided conferences between the representatives of the procuring agency, the aircraft manufacturer and the suppliers of accessories are necessary.

This process may become quite involved and complicated as is illustrated in the following example: Assuming that the procuring agency has ordered a medium bomber of specified gross weight, speed and ceiling. Among others, it was further specified that, without expending unreasonable weight, the plane should be soundproofed in such a manner as to permit "conversation in a normal tone of voice" in the navigator's cabin. This general specification is interpreted by the engineers of the airplane manufacturer through establishing the figures for the maximum allowable noise level and the weight at which it must be obtained.

The supplier of the soundproofing materials and his engineers may now prove that either this weight has to be exceeded or the soundproofing requirements lowered. Since any excess weight must be avoided in order to meet the gross weight limitations while, on the other hand, the aircraft manufacturer does not feel that a lesser noise level reduction would meet the broad requirements for effortless conversation, a compromise becomes necessary. This is negotiated in meetings of the three parties concerned and will usually lead into lengthy discussions and consultations with superiors and experts. Like all compromises, the result of these negotiations will not be entirely satisfactory to anyone.

This example represents a by no means infrequent occurrence, and is typical for comfort accessories which are still too unfamiliar to most people to be sufficiently appreciated. Therefore, it is essential to establish a basis on which a procuring agency can formulate its requirements, the airplane manufacturer can draw its specifications and the supplier of comfort equipment can make his designs.

4.0 PLANNING OF EQUIPMENT

Up to a short time ago it was very difficult to interest manufacturers in the development and production of special aircraft accessories, let alone those pertaining to comfort. Planning of this equipment was, then, quite a task because the aircraft manufacturer had the choice of either buying whatever was commercially available, even though it fell short of his specifications, or he had to develop and build it in his own plant.

Naturally, a manufacturer of such products as temperature controls could hardly afford to initiate lengthy research in order to develop a temperature control for an airplane cabin heater, with the prospect

of selling one or two dozen of them. Instead, he would modify one of his existing controls and pay little or no attention to such contingencies as low air densities and humidities, or high gravitational forces.

Consequently, the procuring agency, the airplane manufacturer and the supplier of the comfort accessories were confronted not only by the problem of agreeing on the requirements for this equipment and the weight and space which was to be allotted to it, but also its detail design or even the principles to be employed. Although similar problems existed for some of the other accessories, they were not nearly as difficult to solve since specialized manufacturers of accessories directly pertaining to aircraft have been in existence almost as long as the airplane itself.

These conditions changed rapidly with the outbreak of the war in Europe. The tremendous quantities of planes which were ordered by the British, multiplied many times after our entry into the war, created an entire aircraft accessory industry. This industry consists of old established manufacturers who set up aircraft divisions for aircraft adaptations of their existing line of products, and new enterprises which were organized to specialize in the production of one or more items for specific airplane use.

This development has been of particular benefit to the comfortization engineer. For instance, before the war it was practically impossible to find suitable aircraft heaters. The systems that were then in use were more or less of an experimental nature and usually gave more trouble than heat. By 1943 there were at least half a dozen manufacturers of aircraft heating systems conforming to most of the manifold specifications for such equipment.

In spite of the fact that the comfortization engineer has now the choice of a number of manufacturers for the equipment he is looking for, and a better understanding on the part of these manufacturers for the specific conditions which must be met, he is still handicapped in his planning because he lacks a firm foundation on which he can base this planning.

Therefore, it is necessary to create a common basis not only for the planning of requirements and specifications but also of equipment. Obviously, this is possible only through the establishment and general use of comfortization standards which are discussed in the following chapter.

V

COMFORTIZATION STANDARDS

1.0 Purpose of Standards

The purpose of standards is to provide a common foundation for individual but similar lines of endeavor and to establish universal rules for the application of related principles. Hence, the task of standards is to substitute a multitude of personal opinions and theories with a single set of rules which are usually based on successful experience.

The conditions for effective standardization in any one field are, therefore, a sufficient collection of empirical data, their compilation by qualified persons and their strict enforcement. If aircraft comfortization is standardized in this manner, it will quickly graduate from the guess and experimental stage into a full-fledged accessory group.

The following outline describes the application of standards to the three phases of comfort planning, as discussed before.

2.0 Standardization of Comfort Requirements

Once comfort requirements are standardized, their selection for a particular airplane should be entirely automatic. In other words, if a procuring agency has decided on such basic factors as size, speed, ceiling and purpose of the airplane which it desires to procure, there should be no need to debate its comfort requirements. If properly standardized, these requirements are easily found by means of an analysis similar to the one described in Chapter III.

There are, of course, cases in which the procuring agency has definite ideas with respect to comfortization, such as the desire for a pressurized cabin. On the other hand, the final decision as to whether a cabin should be super-charged in preference to the use of oxygen equipment, or whether wing anti-icing should be used instead of de-icing, should preferably be left to the aircraft manufacturer.

In establishing the requirements for an airplane the procuring agency should limit itself to those features which pertain, primarily, to the engine and the airframe but not the accessories. If the manufacturer is permitted to select, design and install these accessories in accordance with mutually agreed upon standards, his individual engineering groups—including that of comfortization—will never be stumped by unreasonable requirements and will find their task immeasurably facilitated.

3.0 Standardization of Comfort Specifications

A procuring agency may specify ventilating requirements as follows: "Adequate ventilation shall be supplied to all occupied spaces of the airplane." Obviously, this specification is entirely superfluous inasmuch as it is understood that a flight crew is not supposed to suffocate. In addition, the term "adequate ventilation" may lead to wide speculations.

If, as a result of this, too little air is supplied under certain conditions of flight, the flight crew will experience considerable discomfort. If too much air is supplied, the flight crew may not only have to put up with drafts and other discomforts, but the ventilating system will be inefficient, heavier than necessary and entirely unsuitable. Obviously, there is only one solution to this problem, and that is to establish, once and for all, a clear definition of what constitutes "adequate ventilation."

Similar considerations apply to such vague terms as "adequate illumination" or "reasonable heat." Without standards, it is left entirely to the manufacturer to supply heat or air or light in what he considers to be reasonable or adequate quantities. The problem lands on the desk of an engineer whose task it is to translate these terms into btu per hour, cfm, or foot-candles. Having very little to go by, the engineer will select a figure from a book or a catalog which will usually vary considerably from the results obtained by an engineer of another factory who happened to get his figures from another book or catalog.

The real martyr in this case is the supplier of the accessory equipment because, every time he sells his equipment to another manufacturer, he has to meet different specifications. The result of this method is not only waste and inefficiency but, in many cases, a constant source of confusion for the flight crews and service men.

This situation has long been recognized by a number of responsible parties who set out to solve this most complex of problems in the only possible manner, namely, by establishing standards for aircraft specifications. This work is being carried on by the Society of Automotive Engineers in collaboration with the National Aircraft Standards Committee and the Aeronautical Board, the National Advisory Committee for Aeronautics and other groups who are spending considerable research, time and effort in order to arrive at specifications which apply to all phases of aircraft design.[1]

Once these standards are established and accepted, there can be no guess work in writing specifications. As a matter of fact, it should be entirely unnecessary even to write specifications for comfort equipment, and it should be sufficient to merely state that, for instance, the cabin of an airplane is to be pressurized. The air quantity which has to be supplied in this case as well as the required amount of heat and other factors can then be found in the respective standard sheets.

4.0 How to Arrive at Standards

Standards for aircraft comfortization equipment like most other standards must, of necessity, be broad and general in order to meet all possible contingencies. On the other hand, the standards should not leave anything to the imagination or discretion of the person who uses them in preparing specifications. Inasmuch as aircraft comfort is a very new accessory group, and, actually, not even recognized as such, its standards are not only of a directive but also explanatory nature.

The first step in creating comfortization standards is to consult the people who are interested in the selection and design of this equipment and those people who have to use or service it. Consequently, the following parties must be considered:

4.1 THE PROCURING AGENCIES. These are Army, Navy and airlines. Their interest lies in the assurance that whatever standards for comfort equipment are accepted will neither be too broad to interfere with the other requirements of the airplane, as established by them, nor be too narrow to make the installation of such limited comfort worth-while.

4.2. THE AIRPLANE MANUFACTURERS. The manufacturer must be sure that the adopted standards are adaptable to the particular type of plane or planes he is building, and that he can readily fabricate, procure and install satisfactory equipment within the scope of the standards.

4.3. THE ACCESSORY MANUFACTURER. The industry which supplies the comfort accessories and devices should, of course, play an important rôle in approving standards pertaining to their products.

Failure to do so in the past has either resulted in requirements which these manufacturers could not meet or which were so widely divergent that many products had to be custom-built. Standardization of requirements, however, will enable the accessory manufacturer to anticipate specifications and to develop, produce and deliver standard models faster and cheaper, without fear of rejection or request for changes somewhere along the line.

4.4 AIRCRAFT RESEARCH. The next group to be consulted are those institutions and societies which have made the study of comfort and

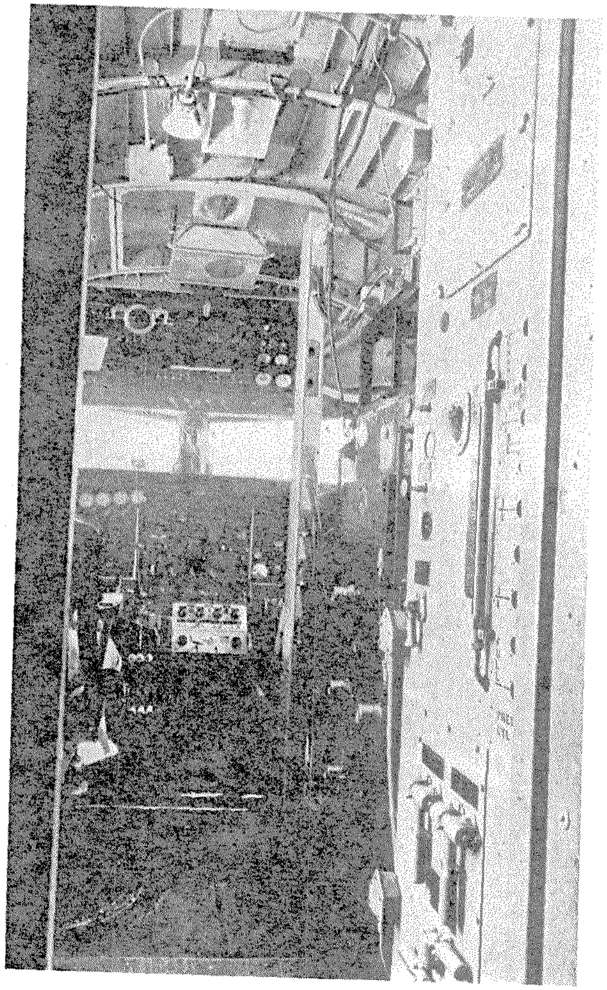


Fig. 17

other accessories their specialty. Among these are, primarily, the National Advisory Committee for Aeronautics, the Guggenheim Institute of Aeronautics and other organizations. The research which has been conducted by these groups and the experiences which they have collected should form the actual foundation for the writing of all aircraft standards.

4.5. FLIGHT CREWS. Another group of people who can contribute valuable advice consists of the pilots and flight crews. No matter how well designed and throughly tested a piece of equipment is, only actual use will show whether it is any good or not. For instance, there is a tendency of incorporating numerous controls, indicator lights and instruments on the panels of equipment which are very desirable in the laboratory and during test flights. However, neither the pilot nor any member of the flight crew has the time or inclination to add the operation and observation of comfort devices to his other duties. Their comments about this and other phases of comfort design should be considered seriously because they are the ones who not only can contribute the most useful empirical data but are supposed to profit the most from this equipment (Fig. 17).

4.6 GROUND CREWS. Men who are responsible for the servicing and upkeep of equipment have enough practical experience to make their suggestions worth listening to. There is quite a difference between regular service in the fully equipped hangar of a large airport, and emergency repairs and service in the desert. Anticipating such contingencies, it is not sufficient to pass up service requirements with phrases like: "Service and repairs must be accomplished in the simplest possible manner and without the aid of special tools."

4.7 PASSENGERS. The next group whose comments are of considerable interest, are the passengers on both commercial and military transports. Zand based his entire work on just such comments and thus created the beginning of aircraft comfortization. Therefore, it is imperative, before establishing the standards of comfort for passengers, to find out what people other than engineers or purchasing agents consider to be a comfortable seat or a convenient berth (Fig. 18).

4.8 FLIGHT PHYSICIAN. Finally, there is one person who is most vitally interested and experienced in physical welfare, and yet has hardly ever been consulted in arriving at the standards for comfort equipment—the flight physician. No matter what other individuals or groups consider comfort, it must be left to the medical profession to determine whether a method for creating comfort is conducive to health and physical requirements of the body. For this reason, the physician

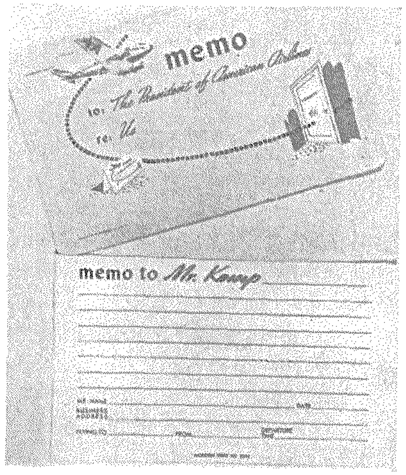
should join the circle of technical, industrial, military and business men in approving standards for comfort.

5.0 SCOPE OF STANDARDS

It is, of course, difficult to write standards which give the comfortization engineer all of the information necessary to specify or design a particular type of equipment and, at the same time, make these standards applicable to all other cases. Therefore, the standards must be limited to the fundamentals of design.

For example, the standards for air supply should specify the amount of air to be supplied under various conditions and similar data which pertain directly to ventilating comfort, such as drafts, stratification and other details. However, they should not specify a particular method of ventilation although they should recommend systems which are commonly best suited for each of a number of cases.

Among many other factors to be covered by standards are the ambient temperatures which are to be the basis for all calculations. This applies also to the definition as to what constitutes sufficient illumination for the performance of certain jobs, establishment of desirable temperatures for all purposes and conditions of flight, and methods of calculation.



memo

to: The President of American Airlines

fr: Us

memo to Mr. Kemp

Fig. 18

Of the greatest importance is an agreement concerning the allotment of weight. While difficult, it is not impossible to establish reasonable percentages of the gross weight of an airplane for allocation to certain comfort devices as there has been enough practical experience with such devices to arrive at rather conclusive figures and percentages. Standards for weight allocations or methods of how to establish them will eliminate unreasonable weight specifications in the future.

Similarly, there must be a foundation on which allocations of space, electric current, etc., can be calculated. Last but not least, standards must incorporate sufficient data on approved accessory equipment such as valves, relays, fabrics and materials, so as to assure their proper selection.

6.0 HOW TO APPLY STANDARDS

Standards as described are already in preparation and partially available at this writing. In addition, there are certain practices which have become unofficially standard over a period of time and can be used pending the completion of an official set of standards. Many of the data and figures given in the following chapters are based on such standard practices and should assist in giving a fair picture of expected performance.

With the aid of temporary or permanent standards, the process of writing comfort specifications becomes a rather simple one. It should consist of the following:

a. The procuring agency forwards its general requirements for the airplane which it desires to procure. It omits all references to comfort equipment save those which pertain to special conditions.

b. The manufacturer analyzes the comfort requirements in accordance with the comfortization type and characteristics of the airplane. This establishes the list and scope of comfort features which must or should be incorporated.

c. Next, the comfortization group consults the standards pertaining to these features. With this information it is now possible to write the specifications which, incidentally, should also be standardized.

d. The specifications are then transmitted to prospective suppliers unless the equipment which they cover is fabricated by the airplane manufacturer himself. As the supplier or sub-contractor is familiar with the standards applying to his product, he is prepared to meet the specifications of the aircraft manufacturer either from stock or a combination of stock items.

* * *

Although this procedure appears to be quite automatic, it does not exclude the need for men who are trained to translate requirements into specifications and to interpret specifications in accordance with engineering practice. This is particularly essential in the planning of comfort equipment which should be the sole responsibility of the comfortization engineer.

REFERENCE

[1] J. D. Redding, "Aircraft Standards for Victory," *SAE Journal*, Vol. 51, No. 4.

VI

THE COMFORTIZATION ENGINEER

It has been a frequent practice among aircraft manufacturers to assign the task of comfortization to unqualified men. The reason was that, up to a short time ago, comfort equipment was not considered as important as other accessories of the airplane. Therefore, its selection and design was left to young men of little experience. Notwithstanding the relative importance of comfortization, it is obvious that the heating and ventilating system of an airplane is better left to an air-conditioning specialist who knows only little about airplanes than with an engineer from the landing-gear group who knows nothing about air conditioning.

1.0 QUALIFICATIONS OF THE COMFORTIZATION ENGINEER

Comfortization must be taken care of by the best men available for this purpose. These men should meet the following qualifications:

1.1 TRAINING: Comfortization engineers must have exhaustive experience in the field which they are to adapt to aeronautics. Thus, the soundproofing of an airplane should be handled by an engineer who has a good background in the soundproofing of ground structures and vehicles. Furthermore, they should be familiar with the conditions existing in and on an airplane. If they have not had any previous aeronautical experience, they should be trained or train themselves in the same manner as designers, draftsmen, inspectors and other specialists are trained for work in aircraft factories. This knowledge or training should consist of fundamental aeronautics, structural requirements of the airplane and other factors pertaining to flight at high altitudes, at low air densities and temperatures. This knowledge is essential as its lack would result in the interference of the comfort equipment with the flying qualities and purpose of the airplane.

1.2 PERSONALITY: The comfortization engineer depends more than most other design engineers on suppliers and subcontractors. Therefore, he must be qualified to negotiate with outsiders and show good judgment in selecting the best of suitable equipment. This requires excellent personal qualifications in addition to professional background.

1.3 FLYING EXPERIENCE: It is very desirable that the comfortization engineer has some solo flying time to his credit. Misdesign of comfort features and unsuitability in practice are often caused by the complete lack of understanding on the part of the designer as to what constitutes comfort for pilots and flight crews (Fig. 19).

Fig. 19

In lieu of solo flying it is, at least, essential that the men who design the comfort equipment for airplanes have participated in a number of test flights in order to see for themselves how their equipment performs. For this reason, every member of the comfortization group should have a minimum of "observation hours" in the air before he is given any responsible assignments. Most aircraft manufacturers give their engineers frequent opportunities to take part in test flights. In addition, both the Army and Navy have always been extremely co-operative in arranging such flights for manufacturers' representatives.

2.0 ORGANIZATION OF THE COMFORTIZATION GROUP

The various features of comfortization have much in common and often overlap to such an extent that they cannot be easily separated.

The ventilating engineer must work very closely with the heating engineer inasmuch as heating and ventilating are often combined. The heating engineer, in turn, must co-operate with the soundproofing specialist since the soundproofing installation has to serve the purpose of heat insulation as well. On commercial aircraft the soundproofing engineer works hand in hand with the stylist who must select his fabrics in accordance with its sound- and heatproofing qualities. The stylist again cannot separate his duties from those of the designer of the seats and berths. The latter requires the advice of the illumination engineer who also assists the designer of the galleys and lavatories. This man depends upon the plumbing engineer for the supply of the water. Finally, the plumbing engineer must consult with the heating engineer concerning heat for water and galleys.

Thus, the comfortization group deals with a number of interlocking jobs. This group should be organized the same as all other groups, headed by a chief comfortization engineer who is sufficiently familiar with all phases of comfort to properly co-ordinate the individual tasks. He should answer only to the Chief Engineer or Chief Project Engineer and, whenever possible, have the final decision as to the selection, disposition and design of the comfort equipment.

3.0 RELATIONSHIP WITH OTHER GROUPS

If comfortization is accepted as a full-fledged design group in the engineering departments of aircraft factories, it should be treated on an equal basis and take part in the design of the airplane from the moment it goes on the board. Only in this manner is it possible to select comfort equipment which always meets the requirements of the airplane and will in no way interfere with its other accessories.

Comfortization engineers all too often are called in when the plane is all but completed and, often, already in the mock-up stage. As a result, ventilation ducts have to be installed in undesirable locations, air scoops increase the drag, lines carrying hot water are close to structures which should not be exposed to heat, seats are cramped, etc.

All this can be prevented, if the comfortization group can work in close team-work with the other design groups, and if its requirements and suggestions are considered whenever compatible with the airplane itself. Finally, the comfortization group should consult frequently with representatives of the procuring agency, the manufacturers of the comfort equipment, pilots, flight crews, service men and other interested parties.

Once all of these conditions are met, the individual comfort features and their scope can be easily established, the specifications written and the equipment selected. Still, the task of the comfortization engineer is not yet completed.

The engineer specializing in aircraft comfortization should not be satisfied with what he has created. Quickly-gained experience in specifying, selecting and designing comfort equipment can easily develop into routine. However, this routine should not be more than the basis for future development. Ambitious dissatisfaction with the results obtained and the desire for greater comfort at less weight should constantly stimulate the comfortization engineer to improve his equipment and, with it, the airplanes which his company and his country are building.

VII

REQUIREMENTS OF AIR SUPPLY

1.0 INTRODUCTION

The analysis of the comfort accessory group, as made in Chapter II, established two separate lists—one for military and the other for commercial airplanes.

The first requirement on both lists is ventilation. It will be noted that this feature is termed merely "air supply" in the military list while, in the commercial group, it is designated by the broader term "air conditioning." This differentiation has been made for several reasons.

"Air supply" is essential for physical existence but refers strictly to quantity. It is defined as "the process of supplying or removing air by natural or mechanical means to or from any space."[1] "Air conditioning" is a desirable comfort, referring to both quantity and quality. The A.S.H.V.E. Code of Minimum Requirements of Comfort Air Conditioning defines it as "the process by which simultaneously the temperature, moisture content, movement and quality of the air in enclosed spaces intended for human occupancy may be maintained within required limits."

If applying these definitions to aircraft, air conditioning of non-military planes is almost exclusively reserved for commercial transports where considerations of weight and cost are not as important as the comfort of paying customers. Private planes and other non-military craft of small size neither permit nor require elaborate comfortization. Air supply on such planes constitutes no problem for the designer as long as proper care is taken to prevent exhaust gases and fumes from leaking into the cockpit, and to avoid harmful drafts as much as possible. Otherwise, the natural infiltration and circulation of air during flight is usually more than sufficient.

Neither is the problem of decreased air density at high altitude a serious factor since most small, non-military airplanes have relatively low ceilings. Where high altitudes have to be considered, the conventional portable oxygen equipment is entirely satisfactory. Consequently, the designer of comfort accessories for commercial planes has to deal mostly with large, luxurious airliners where the air supply should meet all of the requirements as listed in the definition of "Comfort Air Conditioning," including that of heating. In addition, the equipment for ventilating and heating on such planes is so interlocked that efficient design necessitates their treatment as one single comfort feature.

To a certain extent, this is also true for those military airplanes which require evenly distributed, properly heated and well planned air supply as, for example, transports and ambulances or planes carrying photographic laboratories, perishable goods, etc. Most other military planes, however, have requirements for air supply and heating which are so difficult to combine that the comfortization engineer must treat them as entirely different items. Wherever a combination should prove to be possible and feasible, it can be easier effected after all requirements have been established independently so that no premature compromises might lead to inefficient design.

Since it is safe to assume that much of the post-war, commercial air traffic will be at high altitudes, air supply on aircraft in general presents so many problems that a separate analysis is advisable in practically all cases.

2.0 FUNDAMENTAL REQUIREMENTS OF AIR SUPPLY

Before discussing the means and methods best suited for supplying air on planes, it is essential to understand clearly the fundamental requirements of proper air supply. Offhand, the answer seems simple: there must be enough air to furnish sufficient oxygen for breathing to all occupants of the plane. On many military planes, natural circulation, infiltration through numerous openings and, at the most, hand-operated ventilation flaps are relied upon to provide the necessary air quantities.

In reality, this problem is much more complex. The comfortization engineer has to consider:

1. The supplied air must furnish sufficient oxygen for breathing up to the absolute ceiling of the airplane and must be reasonably clean and free of dust, bacteria, etc.
2. It must provide constant circulation, not too rapid to cause harmful drafts yet capable of removing smoke and objectionable odors which increase the tendency to airsickness.
3. It must keep the percentage of carbon dioxide in the air down to a desirable level.
4. It must have sufficient but not too much cooling power to insure the "comfortable maintenance of normal body temperature without undue restraint or demand upon bodily activities."[2]
5. It must provide for proper distribution of both humidity and heat.
6. If air and heat supply are combined, with air being the heat

transfer medium, air must be introduced in sufficient quantities to prevent high inlet temperatures.

7. At high altitudes, it must aid in maintaining a safe pressure around the body.

The quantities, movements and pressures of the supplied air should meet all of the above conditions as the first, basic requirement of aircraft comfortization. While this is usually well taken care of on commercial airliners, "Comfort Air Conditioning" on military planes is mostly neither essential nor possible unless large losses in weight and space are taken into account. However, there are always certain minimum requirements which must be met.

3.0 CALCULATION OF AIR QUANTITY

There are several methods of arriving at the necessary air quantities. The first is to establish the lowest amount of fresh air which effectively provides the chemical needs of respiration. The most common figure used in ground ventilation is 30 cfm of air per person. Mechanical ventilation on some commercial airliners is based on somewhat higher figures while considerably smaller amounts have been proposed and used on military planes. In planning on this basis, it must be remembered that the weight of a given volume of air decreases with altitude while the data for the oxygen needs of the human body are based on the quantity of oxygen, by weight, in each cubic foot of air of sea-level density. Consequently, if the air requirements of the average person are accepted as 1800 cu ft/hr, at an average air density of 0.075 lb/cu ft, it is necessary to supply a greater volume at higher altitudes where the air density and oxygen content are smaller. Therefore, the advisable air requirements are 135 lb/hr/person.

Another way to calculate air quantities is by the air changes per hour necessary to remove smoke, body and other odors, etc. The most rapid air change used on commercial transports is one complete change in the cabin every minute. This, of course, provides much greater comfort and better distribution of temperatures. W. W. Davies reports that, at such a rate, the temperatures in the cabin would not vary more than plus or minus 3°F while, with one air change every two minutes, the temperatures might vary as much as plus or minus ten degrees.[3] On the other hand, rapid air changes require large ducting, scoops or blowers and heat quantities, and might result in drafts which are usually felt when a velocity of more than 2 ft/sec occurs. Therefore, about 30 air changes per hour appear to be a good compromise for commercial transports, while from 12 to 20 changes per hour should be ample for military planes.

A third way of determining minimum quantities is to figure the amount of air needed to keep the carbon dioxide in the cabin down to the accepted standard of 8 to 10 parts in 10,000. The normal content of carbon dioxide in the air is 3 parts in 10,000. The average person breathes out 0.8 cu ft of carbon dioxide per hour, when at rest, and up to 1.6 cu ft when at work (at a temperature of 68°F). If the cubical content of the cabin and the maximum number of persons present in the cabin at any one time are known, it is easy to calculate the minimum supply of fresh air required to keep the concentration of carbon dioxide below the safe limit. This must also take into account the carbon dioxide given off by smoking and the reduction of the effective cabin volume by its occupants, equipment, etc.

The choice of the best method for calculating safe minimum air quantities is by no means arbitrary. Since all of the above conditions must be met, it is necessary to obtain the individual amounts for each one of them and select the largest one which, in most cases, is the amount required for the desirable number of air changes in the cabin.

If air and heat supply are combined, the calculated air quantity must be checked for an additional requirement. Because the air has to transfer a specified amount of heat to the cabin and, possibly, serve other purposes, enough must be supplied to prevent over-burdening of the air with heat, that is, too high air temperatures. Apart from the fact that unreasonably high air temperatures cause discomfort to persons near the air inlets, overheated air blown against parts and equipment made from such materials as plastics or heat-treated aluminum is a serious menace.

Finally, there is one very important check which, unfortunately, is not always made with sufficient thoroughness: The concentration of carbon monoxide in the cabin or cockpit. The large amounts of carbon monoxide in the engine exhaust often result in some infiltration into the ventilating air. Even small amounts cause headaches and inefficiency. Greater concentrations bring about collapse and death in a rather short time. It is of the utmost importance to measure the amount of carbon monoxide in the ventilating air during the first test flights and make sure that it does not exceed the accepted maximum of one part in 20,000 or 0.005 of 1%. Any increase over this figure might be fatal.

While close analysis of all of these problems gives very conclusive data for commercial planes, it has only limited value for the establishment of air requirements on military craft. A well-sealed or even supercharged cabin permits assumptions which do not hold true if cockpit hoods or gun blisters, openings for guns and other equipment allow uncontrollable infiltration of air quantities which are larger than the required minima.

A further difficulty is added by the fact that a bomber, for instance, may have a normal crew of eight persons while an airliner of comparative size may have room for three or more times that many passengers and crew members. Yet, it would be unwise to establish the air requirements for only eight persons, because many additional passengers may have to be carried in emergencies arising from military operations.

Since it is all but impossible to predict the actual air circulation through most military planes of the cabin and compartment types, it must be determined during test flights whether the natural air circulation meets the calculated requirements, if no means for mechanical ventilation are provided.

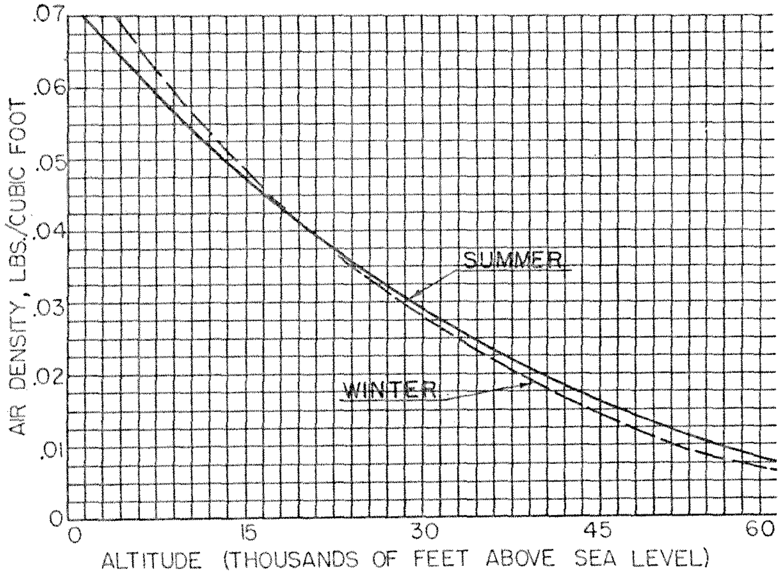


Fig. 20

4.0 Problems of High-altitude Flight

The calculations of air supply for airliners are usually based upon requirements on the ground. This is feasible only for such passenger planes which fly at reasonably low altitudes. However, the tremendous altitude ranges of most military aircraft and the tendency toward commercial high altitude traffic necessitate serious consideration of the various effects of high altitude on the human body, particularly those caused by low air densities.

Figure 20 shows the decrease of air density with altitude. The full curve represents average summer densities at about 40°N latitude in the United States; the dotted curve shows the comparable densities in winter.[4] The densities decrease rapidly, at first, and slower later on, because the lower air strata are under greater pressure from the air resting on top of them than are the higher layers. The warmer air in summer is less dense than the winter air. This difference becomes smaller with increasing altitude and, at about 25,000 feet, the air densities in summer and winter are alike. Curiously enough, at still higher altitudes, the winter densities are somewhat lower than those in summer.

From about 10,000 feet on up the normal person begins to feel the decrease in air density as *anoxemia* or oxygen want. However, different persons are affected differently. Millions of people live in mountainous territory considerably over 10,000 feet high, without being physically or mentally inferior to their brothers in the lowlands. Of course, they are acclimated to living at these altitudes; most other persons will not suffer any discomfort with change in altitude and air density if it is gradual and within certain limits.

Fig. 21

Fig. 22

This is not the case in high-altitude flying where both the rate of change as well as the altitudes reached are usually beyond the physical endurance of the human body. After initial experiences in actual flights—with fatal outcome in a number of cases—ground tests were conducted in decompression chambers (Fig. 21) to study the phenomena occurring at high altitudes and create equipment to make flights at these altitudes possible and even comfortable. This equipment was then taken "upstairs" by experienced test pilots upon whose observations all further developments were based (Fig. 22).

According to collected data oxygen must be supplied for all flights exceeding 15,000 feet for any length of time. Although many persons do not experience serious discomfort up to and, sometimes above altitudes of 20,000 feet, efficiency and power of thinking become increasingly impaired. Numerous fliers complain about hearing losses and, often, disturbing after-effects, particularly if the descent has been rapid. Above 30,000 feet practically pure oxygen must be supplied or unconsciousness and death may occur within 60 seconds. Often, pains in the joints, similar to the bends of deep-sea divers, are experienced if flying at and over this altitude. Apparently, this is caused not so much by *anoxemia* as by the liberation of nitrogen from the blood.

Another consequence of the large decrease in air density is the effect of decreased air pressure on the body. The air column over each square inch of the skin, at sea level and under standard atmospheric conditions, weighs 14.7 lb. Thus, a total weight of thousands of pounds rests on the human body which would be sufficient to crush it save for an identical pressure exerted from within the body which cancels the pressure from the outside. If the outside pressure decreases, a situation arises which, fundamentally, is analogous to that when a person attempts to dive to the bottom of the ocean. The increasing pressure of the water column on top of him will finally be so much greater than the pressure exerted from within the body that the diver would be crushed to death. By the same token, certain deep sea animals which are adapted to living at great depths will actually explode, if brought to the surface.

While the human body can, to some extent, adapt itself to slowly changing atmospheric pressures, grave discomforts and even painful injuries will result beyond certain limits. Many persons feel the unbalance of pressures even at comparatively low altitudes, such as on top of mountains, when they notice this unbalance by a disagreeable sensation in their ears.

This problem is very much aggravated by the great and sudden changes to which military fliers are exposed. With increasing altitude, blood may begin to spurt from mouth, nose, ears and eyes and, even if the breathing requirements are met by oxygen equipment, death might result ultimately from the bursting of overburdened blood vessels and other causes.

5.0 CHOICE OF CEILING

It is not up to the comfortization engineer to specify the ceiling of the plane which he has been called upon to comfortize. Although he has the right and even the duty to point out the complications which every added 1000 feet of ceiling bring about, the establishment of

ceilings is mainly based on considerations other than those of comfort.

However, a study of reports available from all of the warring nations makes it appear likely that a maximum ceiling of about 40,000 feet is just about the limit for nonpressurized, military airplanes used during this war. Although planes with still higher ceilings might be contemplated on either side, the comfortization engineer should be safe enough in accepting 40,000 feet as the upper limit for his calculations.

Commercial air traffic at high altitudes is by no means a post-war dream. Since the middle of 1940 T.W.A. operated the supercharged Stratoliners in scheduled coast-to-coast flights, rolling up the impressive total of 2½ million miles in their first year of operation. The four 1100-horse-power supercharged engines give the Stratoliners a cruising speed of almost 225 miles an hour at three to four miles above the earth. The 33-passenger craft have attained speeds as high as 389 miles an hour when assisted by the strong winds often found in the upper regions of the atmosphere.

There are two basic reasons for passenger flights at great altitudes: smoother flight and greater speeds. After the war, with the expected expansion of private air travel, added safety from collisions will be found at altitudes too great for small, private craft. Although it is still too early to establish the optimum ceiling for high-altitude passenger transports after the war, it appears that about 30,000 feet is a close approximation. Incidentally, present passenger planes equipped for high altitude operate at such heights, for the duration, where no supercharging is required although oxygen equipment is provided for passengers and crew in cases of emergency.

6.0 PROBLEMS OF HUMIDITY CONTROL

Another problem in connection with air supply is that of the humidity in the cabin. Ordinarily, the human body should not be exposed to relative humidities lower than 30% and higher than 60%. Commercial airlines have not considered humidity control a serious problem because the ranges encountered at the normal altitudes were comfortable.

W. W. Davies reports, in the previously cited paper, the results of an investigation conducted by the United Air Lines Research Staff which evidenced that, on the average, relative humidity between 5,000 and 15,000 feet varies from 40% to 64%. He also states that the humidity in the cabin is generally from 5% to 6% lower than that on the outside and that, under normal conditions, relative humidity in the cabin is well within the accepted limits.

Davies then explains that, in order to increase the humidity 10%, it would be necessary to carry 35 lb of water, also diffusing equipment, for a four-hour trip, assuming standard air conditions at 10,000 feet. This, Davies concludes, would make such an installation impractical. If this is true for commercial planes, it is even truer for military aircraft and must, therefore, eliminate the control of humidity for the time being. Even if systems utilizing the water in the engine exhaust for humidification should prove to be practical, humidity control as a pure comfort factor on military aircraft should be considered a luxury.

On the other hand, at altitudes above 20,000 feet humidity decreases very rapidly. The curve in Fig. 23 shows the average percentage of water in the atmosphere at various altitudes for a sea-level temperature of 11°C.[5] At about 35,000 feet this percentage becomes practically zero and then increases gradually up to about 115 miles above sea level at which point it decreases again.

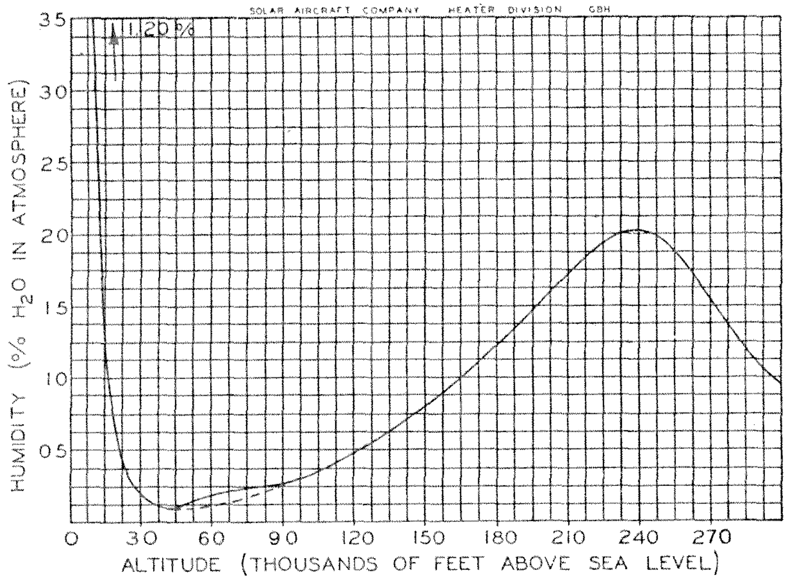


Fig. 23

Evidently, at the altitudes at which the modern military airplane must fly, the moisture content of the air is so low compared to that on the ground that it cannot be disregarded. A plane, brought to medium altitudes from great heights is exposed to fogging of windshields, portholes, gun sights, camera lenses, etc., which may render the flight crew helpless against enemy attack. This sudden and dangerous condensation cannot be avoided easily by scientific humidity control. However, proper heating of the surfaces which are apt to fog up can minimize, if not prevent, this effect. This will be discussed later.

The low percentage and great changes of relative humidity to which the high-flying airplane is exposed have also considerable effect on certain materials and must be considered in their selection and use. Other evidence of how the air supply affects humidity control is shown in a paper by Tomlinson who reports that the weight of the insulation on T.W.A.'s supercharged Stratoliners increased about 35% in 18 months, due to absorption of moisture. This incidentally, amounted to some 160 lb per plane. In planes not supercharged, there was an average increase of only 28% over a period of five years.[6]

It should be remembered that the presence of human beings in an enclosed space increases its moisture content considerably. Mark's *Handbook* states that, according to Pettenkofer, the average hourly production of vapor per person is 0.09 lb for adults at rest, and 0.18 lb for adults at work. Children will produce about half these amounts. The production varies with the air conditions, clothing, etc.

In addition to these effects, the low humidity existing at great altitudes causes dryness and chapping of the skin, burning of the eyes and other discomforts. Unfortunately there is, as yet, no useable method known which will permit humidity control on either military or commercial planes. It remains, therefore, a desirable comfort feature for the airliners of the future in which air conditioning should meet every one of the requirements of complete "Comfort Air Conditioning" on the ground.

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VIII

METHODS OF AIR SUPPLY

1.0 Introduction

Both the requirements and methods of air supply are quite closely related for planes of the same comfortization category. There are, however, several factors which are important in the selection of details. Among these are the service ceiling of the plane, the question of military or non-military use, the requirement of ventilation on the ground, and the possible combination of heat and air supply. Other distinctions and conditions may modify the selected equipment but rarely have much influence on the choice of system.

For these reasons there can be no standard method of air supply which could be adapted to aircraft as a whole or even the individual comfortization types. Nor can there be detailed standards pertaining to the installation of this equipment: One plane of the compartment type might be suitable for overhead ducting while another plane of similar size and design does not permit any ducting at all and must be ventilated and heated entirely differently.

2.0 Means for Air Supply

Just as in air conditioning of ground structures, there are certain devices which have been developed specifically for a similar purpose on aircraft and which, although strictly speaking cannot be classed as standard equipment, are generally accepted as such. The first question is whether to use natural or forced ventilation, or a combination of both. The latter, incidentally, is the most common.

Natural ventilation can be effected by (a) Infiltration, (b) Ventilation Flaps, (c) Ventilation Scoops. Forced ventilation is obtained through (d) Blowers or Fans, (e) Oxygen Equipment, (f) Supercharging.

The following analysis will briefly describe the various means listed above.

2.1 natural infiltration. Most small, private as well as military planes of the cockpit and cabin types are so designed that the natural circulation of air through the cockpit or cabin provides ample air supply. The air can easily enter through the hood of the cockpit type plane, or cracks and other openings of the larger craft. By the same token, used air is drawn out of the plane through openings located in a negative pressure area of the fuselage. These processes are termed "Infiltration" and "Exfiltration," respectively, and constitute a very simple form of natural circulation.

Although this method does not require added equipment and, often, supplies at least the essential air needs, it has numerous disadvantages. First of all, it does not permit any control over the air flow and may result in either too little or too much air supply. While the former is entirely unacceptable, the latter is highly objectionable inasmuch as it causes drafts and complicates the heating installations. If no heaters are provided, cabin temperatures may often be too low for comfort.

Another disadvantage of natural ventilation is the difficulty of anticipating even approximate values for air circulation under various conditions of flight. While tests might show the circulation to be adequate for the normal crew complement, it may be utterly insufficient, if and when emergency passengers have to be carried. Accumulation of odors, carbon monoxide and dioxide, moisture etc. is a further shortcoming. Ground ventilation can be obtained only by opening hatches and doors which may not be desirable at low temperatures. Heating must rely entirely on spot heaters, although central systems are much more efficient on larger planes.

Yet, this type of ventilation is quite common because it is the simplest method known and entails no accessories nor considerations for their installation, operation and servicing.

2.2 ventilation flaps. Usually supplementing natural ventilation, adjustable *flaps* in the ceiling of the cabin serve the purpose of providing additional air, when needed, and, more often, cooling in hot weather. The flaps are hinged and operated manually. If not in use, they are flush with the skin of the plane. At about 45° they deflect a maximum of air into the cabin. In order to make them as small and efficient as possible, they should be installed in a highly positive pressure area of the fuselage. Another consideration in selecting their location is the need of avoiding drafts for persons who are regularly stationed near them.

The advantage of ventilation flaps is their simplicity of design and operation. They can provide considerable amounts of fresh air and, by thus increasing the pressure within the cockpit or cabin, force a higher rate of circulation. Their disadvantages, however, cannot be overlooked. The full-open flap increases the drag of the plane which is particularly objectionable at greater speeds. Furthermore, the flap does not keep out dust and rain or other objects encountered in flight. In addition, it permits little or no control over the air flow and may cause unavoidable drafts, even to the point of blowing charts, papers and the like through the cabin.

As the simplest means of additional air supply and cooling, the ventilation flap can be employed to advantage in combination with natural ventilation.[1]

2.3 SCOOPS. Ventilation *scoops* may be used in two different ways; like flaps as individual scoops in the ceiling and, occasionally, in the walls of the fuselage; or as central air supply in connection with a ducting system.

Individual scoops are, essentially, little different from flaps and have similar advantages and disadvantages. Their main advantage over the flap is the fact that, while not adjustable, they cause less drag because they are properly faired. Figure 24 presents such a scoop. The air is rammed into it so as to set up a slight pressure within the scoop body which acts as a small plenum chamber, reducing pulsations. The bottom of the scoop may be slightly tapered toward the back which assists in "shoveling up" the boundary layers of air near the skin and increases the efficiency of the scoop. Dampers or valves must be added to permit regulation of the airflow. Furthermore, filter screens and rain eliminators may be provided, if necessary.

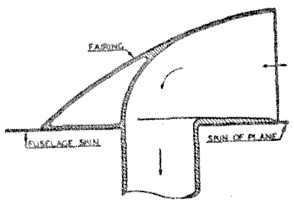

Fig. 24

When the scoop faces away from the direction of flight, it acts as a spill. It is always desirable to use both scoops and spills together so that proper circulation is assured and not dependent on exfiltration alone. By the same token, it is usually advisable to have fewer spills than scoops in order to provide a slight excess pressure in the cabin. Installations of this kind are not uncommon, even in large transports where ten and more scoop-spill combinations are used.[1]

The size and number of scoops depends entirely on the air requirements, the cruising speed of the airplane and the back pressures in the system. If these factors are known, conventional calculations will yield the desired data. Short ducts or *risers* may connect the scoop or spill with the interior of the cabin.

In contrast to the ceiling or individual scoop, the *central scoop* is always the first component of a ducting system. In most cases, it is located in the leading edge of a wing or another area of very high positive pressure. It is an integral part of the skin and, essentially, nothing but a hole in it with softly rounded and, sometimes, flared edges. A tapering tube or transition piece serves for attachment of the

duct. The shape of the scoop hole is adapted to the contour of the adjacent fuselage. Scoops in the wings are normally eliptical. Calculation of their areas will be discussed shortly.

The use of central scoops has many advantages over the previously discussed means of air supply. If properly designed, such a scoop will add considerably less drag than, for instance, an equivalent number of flaps or ceiling scoops. It facilitates the installation of filters and rain traps. Most of all, it permits complete control over the air flow and its distribution. This is of great value, if both the air and heat supply are based on a central system.

The attached ducting system may be very short and merely serve to guide the scooped-in air into the cockpit or cabin. It may also be quite complex and have numerous branches, terminating in warm- or cold-air distributing means. As a whole, air supply systems using central scoops are very flexible and adaptable to almost any condition. Therefore, they should be considered seriously even where requirements of air supply are quite moderate.

2.4 FANS AND BLOWERS. The operation of flaps and scoops is entirely dependent on the ram effect of the air during flight. If ventilation or air supply for a heating system is necessary on the ground, "natural ventilation" must be supplemented or replaced by "forced ventilation." This requires the use of fans or blowers, and electric motors.

Naturally, devices of this type are not very desirable on an airplane, not only on account of the weight and space they take up but also because of the added service requirements and the large electric currents which some of them consume. Yet, it is often necessary to sacrifice weight, space and current for other gains, particularly if these devices supplement other equipment.

Small fans are often component parts of spot heaters, serving to force air through a heat exchanger. Fans are also used in connection with anti-frosting by blowing warm air against windshields and portholes. There are frequent cases in which air streams must be directed against specific objects for either cooling or heating.

On the other hand, every motor represents a source of potential failure and one more item which requires servicing. The air streams produced by fans are not readily controlled and may cause drafts or other undesirable air movements. The revolving fan in itself, unless well enclosed, is a potential hazard. In many cases, the individual fan can be replaced by some more suitable means.

This is not true for the blower. Undoubtedly, there is nothing to take its place in ground ventilation and heating, let alone supercharging which will be discussed later. The question here merely is whether the same blower should be used in the air or whether air supply during flight up to moderate altitudes should be furnished by natural ventilation. Although this question cannot be decided summarily for all cases, it is usually preferable to operate the blower only on the ground since its current consumption is quite high. There are, however, several exceptions where blowers must be used both on the ground and in the air.

For instance, the back pressure in the air distribution system may be so great that scoops and ducts would have to be unreasonably large to cope with the existing ram pressure. In this case a blower may be the only solution. This applies also to certain heating systems which require rather high pressures to assure the necessary air flow. Internal combustion type heaters may need a small blower only for the combustion air while the ventilating air can be supplied by a scoop of moderate size.

In planes travelling at very high speeds the scoop openings with their inherent drag are sometimes a greater disadvantage than the weight and current consumption of a blower. Often, operation at extremely low temperatures makes it desirable to resort to partial recirculation which again requires the use of a blower in the air but results in reduction of the heating plant.

The decision as to whether a blower should be installed at all and whether to use it in the air or not, must be based on the following considerations: First, is ground heating mandatory and, if so, must it be furnished by a source which is a component accessory of the airplane? Second, is recirculation desirable? (The answer, if possible, should be: no.) If so, should it be taken care of by individual fans or a central blower? (Fans for this purpose are almost exclusively used in spot or unit heaters.) Third, can the required pressures be supplied by the ram during flight? (This must be answered by calculating the backpressures in the air-supply system and determining whether the calculated scoop and duct sizes are acceptable or not.)

The designer should try to eliminate the use of blowers during flight whenever feasible, with the exception of those for supercharging purposes. Although it might seem unreasonable to carry the weight of a blower and not use it, it should be borne in mind that the current drain of a blower large enough to meet all air needs, is a serious problem. In addition, it is dangerous to rely on mechanical equipment alone for the vital supply of air since its breakdown would be a tremendous handicap, particularly on the military plane.

Ground ventilation should be provided for only if it is absolutely essential to keep a heating plant operative. Commercial transports

avoid the need for an integral blower by the use of ground air conditioning equipment as shown in Fig. 25. Such facilities are, of course, out of the question for military aircraft which, therefore, must be equipped with blowers as part of a ground-heating installation.

2.5 OXYGEN EQUIPMENT. The atmosphere consists of about 79% nitrogen, 21% oxygen, 0.04% carbon dioxide and a small quantity of other gases. The oxygen is what the human body requires. As the density of the air decreases with increasing altitude, the percentage of oxygen still remains at 21% however, its density or weight per cubic foot of inhaled air decreases with the rest of the gases.

At 12,000, for instance, the weight of oxygen in each cubic foot is only 64% of what it is at sea level. From this point on the average human being gradually feels the deficiency of oxygen or *anoxemia*. In order to make it possible for a person to exist at this and greater altitudes, it is necessary to increase the percentage or partial pressure of oxygen in the air.

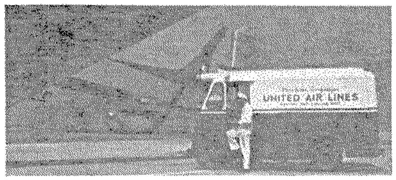

Fig. 25

The effects of anoxemia vary for different persons and conditions, so that it is difficult to establish a sharp borderline beyond which oxygen supply is necessary. Also, oxygen want is somewhat cumulative, that is, within certain limits a small deficiency over a period of time has effects similar to a larger deficiency over a shorter period. The former is more dangerous because it is not felt as urgently as the latter, but will result in increased mental and physical fatigue which is of particular disadvantage to the military flier.

For this reason, it is desirable to agree on definite rules for the use of oxygen supply which are based on experience and should be enforced under all circumstances. According to generally accepted practice oxygen equipment should be used at all times when flying above 15,000 feet, even for brief periods; above 12,000 but under 15,000 feet if exposed for more than two hours; and above 10,000 but under 12,000 feet for flights of six hours' duration or more.

The earliest oxygen apparatus consisted of a bottle filled with liquid oxygen and a hose with a mouth piece which the user held between his teeth. This method did not allow for regulation of the pressure of the evaporating oxygen to any extent, nor was its low temperature conducive to comfort and health although, in some installations, the gaseous oxygen could be preheated.

Modern oxygen equipment consists, essentially, of a bottle containing gaseous oxygen under pressure, pressure regulators and a face mask with connecting hose, as shown in Figs. 26 and 27. Regulation is simple and foolproof, and masks are designed to give their wearer the greatest possible comfort. Equipment of this type will permit physical existence up to extremely high altitudes.

However, in spite of these improvements, the use of oxygen apparatus presents many problems. The first one concerns the choice of pressures under which it is to be bottled. There are, at present, two standard pressures in use. In the *high-pressure* system oxygen is bottled at 1800 psi and, in the so-called *low-pressure* system, at 400 psi. Both systems have distinct advantages and disadvantages.[2]

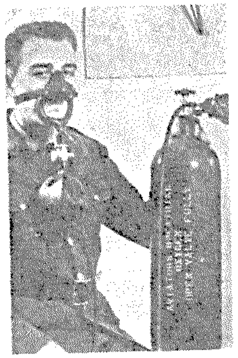

Fig. 26

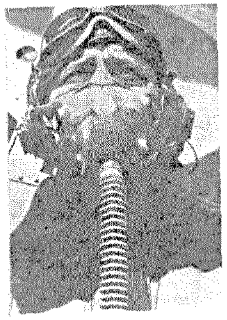

Fig. 27

In the low-pressure system four and a half times as many bottles are required to store the same volume of oxygen as with the high-pressure system. On the other hand, the latter entails definite hazards to plane and crew because the high-pressure oxygen containers tend to explode under the impact of 30- or 50-caliber bullets. This danger can be minimized by armoring the containers, but then the increased weight of the armored bottle offsets any weight advantages over the lighter, low-pressure bottle.

This leaves space as the only advantage of the high-pressure system. Even this advantage is dubious inasmuch as that much more oxygen would be lost, if one bottle were destroyed.

Oxygen containers are now subjected to rigorous tests before acceptance for military planes. In general, it appears that the high-pressure system is suitable for small, non-military planes while the low-pressure system is favored on military as well as large commercial aircraft.

Another choice which the designer has to make is between the *individual* and the *central* oxygen supply. The individual supply is preferable on cockpit planes where no movement of the crew or passengers is required nor possible. Central supply is usually desirable on cabin and compartment types of planes. It consists of a central source of oxygen which is piped through the cabin. At various stations, there are outlets into which the occupants of the plane can plug in. This relieves them of the burden of the heavy equipment and even allows them a certain amount of freedom of movement since the supply hose between outlet and mask can be of considerable length. On the other hand, in moving from one station to the other, the brief time required to get to the next outlet and plug in, or fumbling of the supply hose may have fatal consequences. Furthermore, damage to the central source would shut off the oxygen supply to the entire crew. Finally, damage to the supplying pipes might permit oxygen to mix with oil vapors which would result in spontaneous combustion.

In spite of these shortcomings, central oxygen supply is favored on large, military planes although it should always be augmented by a number of small, portable units held in readiness for emergencies. One variation of such equipment is the so-called "Bail-Out Bottle," which is very light and compact, and intended for use by fliers bailing out at great altitudes, particularly from supercharged planes.[3]

Regular use of oxygen equipment on commercial planes is not recommended. The correct wearing of the mask and operation of the equipment by passengers is a constant source of worry for the crew. Nervous and young passengers often consider it a distinct discomfort. Before all, the psychological effect of oxygen equipment in itself lessens the feeling of security which the airlines attempt to impart to their customers. Therefore, oxygen apparatus should be used on commercial transports only in emergencies and be carried merely for this purpose. However, if its frequent use is necessary, it is advisable to choose a central, low-pressure system.

2.6 SUPERCHARGING. The partial pressure of the oxygen in the atmosphere at sea level is 159 mm of mercury out of a total pressure of 750 mm, or 21%. At 35,000 ft, 73% of the breathed-in air must be oxygen to obtain the same partial pressure as at sea level. This is the principle on which oxygen apparatus is based. However, above about 45,000 ft even the supply of pure oxygen does not permit physical existence anymore.

Consequently, man can exceed this altitude only by building an air- and pressure-tight enclosure around himself into which he pumps air under enough pressure to achieve sea-level conditions, no matter how high he goes. This process has been termed *supercharging* or *pressurization,* and is quite similar to the supercharging of airplane engines.

There are, naturally, many schemes which have been suggested to cope with the high-altitude problem, such as "pressure suits" similar to those worn by deep-sea divers. None of these schemes have gone beyond the experimental stage, at best, while the supercharging of cabins has been developed to such a stage of safety that it has been adopted for commercial passenger flight.

Although the design of the supercharging equipment itself is beyond the scope of this analysis numerous questions enter into the selection of supercharging which are worth discussing.[4] The first question pertains to the need or usefulness of pressurization for military purposes.

If a plane is expected to surpass the limit of 45,000 feet pressurization is essential. Even far below this limit supercharging is superior to oxygen supply in many ways. For instance, the low pressures existing at high altitudes neither provide the necessary oxygen nor maintain a safe pressure around the body. This problem is entirely solved by cabin supercharging. Another and most important factor is the *rate* of pressure changes. Although the body can acclimate itself to gradual changes of outside pressures, serious discomfort and injuries result, if these changes are as great and rapid as they are in military flying. Here again cabin supercharging solves the problem either by maintaining the same pressure at all times or providing for changes which lag so far behind the outside changes that they are not harmful.

One of the principal advantages of supercharging is the fact that the occupants are entirely free of the burden of personal equipment, and have absolute freedom of motion within the cabin. It should also be mentioned that, during compression of the air to its desired density, it is so heated that little or no added heat is required to maintain the cabin at comfortable temperatures.

Offhand, supercharging thus appears to be the logical solution to the high-altitude problem. While this is very nearly the case for commercial aviation, the picture is less favorable where military airplanes are concerned. Supercharging requires a special fuselage design which is not always compatible with the military purposes of a plane. Although the weight of the pressurization equipment is usually not greater than that of comparable oxygen equipment, its current drain is high and servicing more complex. Guns must be normally fixed and, if flexible, operated by complicated remote control apparatus.

Another point is that supercharging equipment on commercial airliners can be very thoroughly checked and serviced before each flight. If, in spite of that, something should go wrong, the plane can drop to altitudes where no supercharging is required and, in the worst case, come down for an emergency landing. The military plane, however, cannot always be minutely checked before each take-off and, if its supercharging equipment fails, dropping to safe altitudes or emergency landings are rarely feasible or even possible.

Worst of all, the supercharged bomber or fighter is quite vulnerable to gun fire from enemy planes flying at similar altitudes. Holes torn in the sealed cabin which, ordinarily, would be of little consequence, might force the plane out of action. To a certain extent, this can be taken into account by a supercharger of enough excess capacity to cope with such contingencies, and by providing devices for the rapid plugging of reasonably small holes, as well as installation of emergency oxygen apparatus.

Nevertheless, as long as the very physical existence of the crew depends on the operation of the complex supercharging scheme in its entirety, the large target of the cabin itself is a serious military disadvantage. For these reasons, supercharging of military planes, although very desirable in many other respects, is quite exceptional.

None of these considerations present much difficulty in commercial planes. One of the latest examples of high-altitude transports, thus equipped, is the huge *Mars,* a flying boat built by Glenn L. Martin Company (Fig. 28).

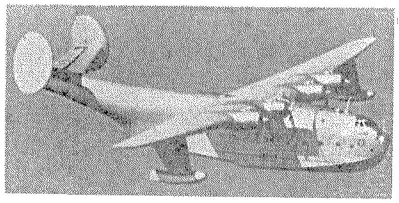

Fig. 28

This plane is so large—its hull has the volume of a fifteen room house and it carries a crew of thirteen—that it is impractical to pressurize the entire cabin. Supercharging is, therefore, confined to the portion forward of the wings and comprises the flight deck and larger part of the main deck. A decompression chamber is provided which permits passage from the pressurized to the unpressurized area and vice versa without too rapid a change in air pressure. In addition, oxygen stations are distributed throughout the cabin for emergency.

As stated before, there is no supercharging on commercial planes for the duration. However, it is expected that a large part of commercial post-war traffic will be handled by supercharged planes. This applies also to such civil aircraft as must operate regularly at altitudes above 15,000 feet.

It is, therefore, wise for the comfortization engineer to prepare himself for this development. Although he is not directly responsible for the supercharging equipment in its details, he must bear in mind that this scheme requires a fuselage which must be strong enough to withstand the great difference in pressures at high altitude, and be absolutely airtight. The fuselage preferably should be cigar-shaped, with circular cross sections throughout. The streamline effect should be carried out from nose to tail to give the plane the required structural stability.[5]

It is not necessary to maintain the pressure inside the cabin at sea-level conditions. Pressures equivalent to those existing at from 6,000 to 10,000 feet are the usual choice of designers who thereby effect a considerable saving in the weight and space of the supercharging equipment. The choice between the lower and higher values depends on the various limitations imposed on the designer. However, 8,000 feet is always a very acceptable compromise.

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IX

METHODS OF AIR DISTRIBUTION

1.0 Introduction

There is a certain analogy between a ventilating system and an electric circuit. The latter consists, basically, of three components: the source of electromotive force, the resistance and the connecting wires. By the same token, a ventilating system consists of a source of air pressure—that is, scoops or blowers—the outlets and the connecting ducting.

Continuing the analogy, there must be sufficient air pressure to furnish the required air current to the outlets against the resistance within the entire system. There, however, the analogy stops. Unlike electric current, air is subject to compression and rarefication. Within the same air space, different layers may be of different density and temperature, and may have different velocities. With increasing altitude, air densities decrease, and back pressures increase for the same mass flow of air. Obviously, these properties aggravate the task of ventilation and must be considered by proper design of the air distributing system.

2.0 Design Considerations

In particular, the following factors require the closest attention:

2.1 drafts are interpreted as local sensations of excessive coolness, and even while very high air movement in relatively warm air increases the rate of heat loss from local parts of the body, it may improve the comfort of the occupant, so long as that part of his body surface is not excessively cooled.[1]

The A.S.H.V.E. *Guide* states that, "during the heating season, air velocities in excess of 20 to 30 fpm usually give undesirable effects. With summer cooling and air conditioning higher velocities up to 40 or 50 fpm, if properly controlled, seem to give satisfactory conditions free from sensations of draft, while with higher ambient temperatures even higher air velocities may be used."

In addition to these factors, the physical constitution of the individual plays an important role in determining whether a movement of air is felt as uncomfortable draft or desirable cooling. Some persons will complain about the slightest air movement and actually suffer ill effects while others seldom or never experience discomfort when exposed to even strong drafts. Therefore, it is practically impossible to standardize air velocities which are acceptable for all persons and under all conditions.

It would, of course, be preferable to keep these velocities so low that even the most sensitive passengers would have no cause for complaint. On the other hand, this would require ducts large enough to permit the movement of the necessary air quantities at very low speeds. Obviously, such a solution is not feasible on an airplane where space and weight are at a premium. For these reasons, the Aircraft Standardization Committee of the Society of Automotive Engineers recommends a maximum allowable air velocity in any one direction of 100 fpm which appears to be the best possible compromise, particularly, if distribution and location of air inlets are properly planned.[2]

2.2 STRATIFICATION, that is, existence of sharply divided layers of air of different temperature, density or velocity is as harmful as drafts. This is not at all uncommon in aircraft ventilating systems and is usually caused by insufficient and uncontrolled air movement which permits such layers to form and exist. As a result, the passengers' feet may be excessively cold, their bodies just comfortable and their heads surrounded by air which is too warm.

Closely related to stratification is the presence of hot or cold air pockets in various parts of the cabin. In all of these cases, it is necessary to examine whether there is sufficient air movement and whether the air inlets are correctly placed. In designing the air distribution system it is, therefore, advisable to draw lines representing the expected flow of air in a picture of the cabin and ascertain whether this flow meets all requirements of good air distribution.

2.3 NOISE. One of the most frequent deficiencies of airplane ventilating systems is the noise which they produce. As will be shown in a later chapter, it is essential to keep noise out of the cabin and also to minimize its generation within the cabin. The whistling and drumming caused by rapid air flow through the ducts is among the worst offenders in this respect.

Naturally, the designer tries to keep the ducts as small as possible. This, in turn, requires high air speeds within the ducts and resulting increase in air noise. Apart from the use of sound-dampening materials in the ducts and appropriate design of elbows, dampers etc., it is essential to arrive at a compromise between optimum duct size and noise prevention. Practice has shown such a compromise to be quite satisfactory, if air velocities in the ducts are limited to 1200 to 3000 fpm.

The lower limit is advisable for commercial transports on which the requirements for noise reduction are considerably stricter than on military aircraft. However, even this figure is too high unless the ducting system in its entirety is properly designed.

Higher velocities are permissible on military planes in order to further reduce duct sizes. Although noise prevention is not as critical as on non-military planes, it would be unreasonable to spend any weight for a soundproofing installation and then impair its efficiency by a noisy ventilating system. Thus, air speeds in ducts must be kept to the lowest possible figure, and higher speeds should be selected only for normally unoccupied areas, such as in the wing ducts which carry air for anti-icing. Care must be taken, however, to prevent transmission of noise from these areas to those which are soundproofed.

2.4 INSTALLATION is of the greatest importance. Badly planned ducts and inlets will not only increase noise, drafts and stratification but also interfere with the functions and movements of the crew, comfort of passengers, operation of other accessories etc. Warm air inlets particularly, must be very carefully located and should always face the largest possible space free of such objects as might act as baffles and deflectors and also those which should not be exposed to the impact of hot air.

Ducts should be so located as to avoid bumps and lowering of the necessary head room. They should be guided close to a rigid structure to which they can be firmly attached. Sharp corners and bends must be avoided as they increase back pressure or the tendency for noise. Dampers and other air flow controls must be easily accessible, and readily removable for repairs and adjustment. Ducts located behind panels or the interior fabric, must be accessible and removable. Ducts require service as much as any other components of an airplane and such service should not require tearing down of lining or parts.

Ducts should be inspected regularly for accumulation of foreign objects, dust and excessive moisture.

The placing of inlets is a science in itself. This becomes particularly obvious in such cases where it is necessary to provide a warm-air inlet serving four seated passengers during the day and two passengers lying in a lower and upper berth at night. Here again it is advisable to make a diagram of the expected air flow and examine whether the circulation follows the desired pattern.

The location of air inlets is even more critical on military planes. If and when high air speeds must be used, inlets should be so placed as to avoid blowing against papers, charts, etc. which are lying loose on tables, or against persons stationed near them. For the sake of economy it is also often necessary to employ high inlet temperatures. In these cases, the inlet must be positioned far enough from materials and devices which may not be exposed to heat.

2.5 QUALITY OF AIR taken in during flight is usually satisfactory for ventilating purposes without further treatment. Humidity control, as explained before, must be disregarded, nor is it absolutely necessary to provide filters unless a plane operates regularly in or over dust-laden territory. Filters increase the back pressure of the system but are recommended, if such an increase can be dealt with easily. Rain and water traps with proper drain are often mandatory, especially on flying boats; they should be inserted right behind the intake scoop.

It is very important that the circulated air is fresh, clean and invigorating. Recirculation is, therefore, not desirable; if resorted to, it should be limited to a maximum of 20%. Obnoxious odors, fumes, gases and smoke cause considerably more discomfort in an airplane cabin than on the ground and their removal is not aided by recirculation although a saving in the heating requirements can thus be obtained.

In normal passenger flight the varying density of the air need not be considered as long as scoops and ducts are designed for the air volumes to be handled at the service ceiling and at, the most, 10,000 feet. In planes with higher ceilings, calculations for duct sizes should be based on the latter figure since air supply above this altitude must be furnished either by oxygen equipment or supercharging.

Air ducts for purposes other than ventilation, such as hot air anti-icing, should always be designed for the air volumes at the maximum ceiling, unless blowers are used.

2.6 CONTROLS for air flow may be fixed, semi-adjustable or adjustable. Fixed controls in ducts and inlets are used for balancing the air distribution during installation and initial testing. If occasional re-adjustments are necessary, semi-adjustable controls should be employed but secured against tampering by unauthorized persons.

Manually adjustable controls are commonly used in connection with individual air supply, such as flaps, ceiling scoops or individual fresh air inlets. If used in a central air-supply system, operation by passengers must be avoided. Controls of this type are mostly automatic with manual override and part of heating installations which will be discussed later.

The control devices differ but little from those used on the ground. They are, of course, considerably lighter and more compact, although positive operation must be assured by sturdy yet simple construction which takes into account vibrations and gravitational stresses. Before inserting controls into an air distribution system, the comfortization engineer must examine again and again whether each control is absolutely necessary and, if so, whether it is designed for lowest possible pressure drop.

3.0 DUCTING

Extensive ducting in airplanes is usually frowned upon because it entails undue sacrifices in space and weight.

Military planes of the cockpit type require no ducting for ventilation although wing ducts have to be used for hot air anti-icing. Small, private cabin planes do not employ any ducting either. Military cabin planes usually have no ducts, and even many compartment-type craft are believed to be better off without them.

Yet, while air ducts are quite difficult to place in a military plane, it will be found that it often pays to take the required space and to overcome reasonable obstacles for the advantages offered by a well-planned ducting system. This is the case on military planes which have to operate at medium altitudes, over long ranges and with large crews—possibly with emergency passengers—and which require a complex heating installation. On commercial transports a ducting system is always advisable and usually necessary.

The advantages of ducting are numerous. It permits the use of a central air and heat supply which saves weight, space and facilitates servicing. It also gives excellent control over air distribution and is practically the only effective method of avoiding drafts, stratification and pockets. Furthermore, it simplifies heating of accessories, anti-frosting and other tasks of heating.

3.1 CONSTRUCTION OF DUCTS. Airplane ducts are mostly rectangular, with the flat or wide side facing the cabin. In many cases, they are made from thin-gauge aluminum and connected by means of tape. In order to prevent metal ducts from drumming, particularly at high air speeds, they should be lined with a layer of felt, about ⅛″ thick, glued to the inside and protected by aluminum gauze or mesh.

Sometimes, balsa wood is used as duct material although this has not always proven very desirable. A design of growing popularity employs aluminum mesh wire which is supported by stiffeners every few feet and covered by doped airplane fabric or similar materials. This construction has the advantage of being very light, adaptable to curving and noise reducing. In commercial planes it lends itself very well to blending into the general artistic scheme. It is, of course, not quite as rigid as metal ducting which must be taken into account in its attachment.

Flexible hose of aluminum or fabric is employed for branch lines carrying small amounts of air around complicated contours. It is usually somewhat heavier than the ducting described above and has a higher resistance to air flow. However, its flexibility and rigidity make it desirable for such purposes as individual fresh air supply and accessory heating.

In attaching ducts it is not sufficient to use conventional brackets and wire suspensions. The vibrations and gravitational forces to which aircraft accessories are exposed demand very rigid attachment to avoid excessive rattling and even breaking, of the duct.

Insertion of a plenum chamber often assists in counteracting the effects of ducts which, because of space limitations, have to be underdimensioned.

4.0 Air Inlets

The choice and location of air inlets presents comparatively little difficulty where the inlet is in direct communication with the outside as is the case with individual flaps or scoops. The only rules to be followed concern structural considerations, the need for positive pressure and the comfort of crew or passengers.

If the inlet is part of a ducting system which has to serve a number of other inlets, several additional problems enter into the picture. The first question to decide is whether the system should be an overhead system or not. In the overhead system the duct is attached to the ceiling of the cabin and provided with grilles or diffusers through which the air enters the cabin. Air outlets or vents are usually located near the bottom and in such a manner that several outlets connect to a common *riser* through which the used air is spilled overboard. In other systems this process is reversed, and fresh air is supplied through grilles or louvres and ducts which are located in the corners formed by floor and sidewall, with outlets in or near the ceiling.

Both methods have advantages and disadvantages. The overhead system permits the use of only one duct along the ceiling while the other method requires, mostly, one duct on each side. The former saves duct work as the connecting ducts to the inlets can be held quite short. Since the possibility of draft decreases with increasing distance of air inlets, their location near the ceiling is very desirable. In addition, such a scheme assures better air distribution and minimizes the danger of incoming air being short-circuited into the outlets before it can circulate within the cabin.

Disadvantages of the overhead system are the possibility of insufficient heating near the floor and the forming of pockets under seats and berths. In many cases structural limitations are such as to eliminate an overhead system entirely. In spite of that, this system should be employed wherever possible and, preferably, in conjunction with diffusers.

The floor board or sidewall type of system is usually easier to install. However, it has the disadvantage of often causing too much draft or heat to the feet and bodies of seated passengers, and complicating an even heat distribution. Travelling along the walls of the cabin, the air may easily short-circuit into the vents and cause turbulences and drafts. These factors must be taken into account, if structural considerations make the choice of this system mandatory.

Short-circuiting into the vents is also the principal disadvantage of warm air inlet grilles located in the window frames. This method is sometimes used since the window panes cannot be protected by heatproofing materials and thus represent the coldest areas of the cabin interior, causing discomfort to passengers seated near them. In spite of that, window inlets are not recommended.

The inlets themselves may be grilles or louvres. The latter are preferable since they are adjustable; this assists in balancing the air supply and distribution. However, adjustment by passengers and unauthorized crew members must be avoided as this could easily offset the balance, and result in increased or decreased air and heat flow through other inlets.

The most desirable forms of air inlet are air diffusers such as the so-called *anemostats.* These units are usually mounted near or on the cabin ceiling and diffuse the emitted air over a wide cone and in such a manner as to practically eliminate the possibility of drafts, even at relatively high air speeds. If used in combination with a heating system, an anemostat like the one in Fig. 29 sucks in cold cabin air, due to its inherent aspirating effect, and mixes it with about twice that much hot air before emitting the latter. This permits higher

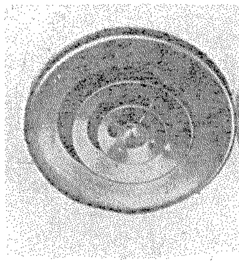

Fig. 29

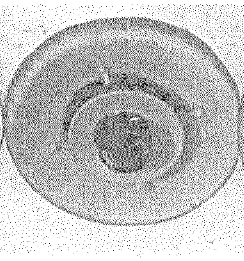

Fig. 30

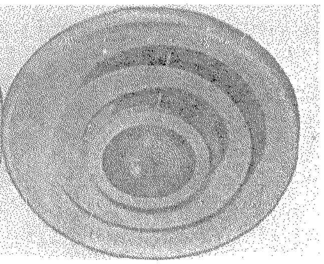

Fig. 31

inlet temperatures and a more efficient all-around heating and ventilating system. Other models combine the diffuser with an exhauster, eliminating the need for additional foul air openings and floor ducts.

The anemostat shown in Fig. 30 is a combination warm and cold air diffuser which makes it possible to adjust the air supply to any temperature from very cold to very warm. Figure 31 illustrates a diffuser with built-in light fixture, allowing for supply of both air and light from the center of the cabin or compartment ceiling.

Diffusers of this type are very common in ground air conditioning. They are light, simple and compact and should be considered for use on aircraft as long as ducting to individual air inlets is at all possible.

4.1 INDIVIDUAL COLD-AIR SUPPLY. Ventilating systems on transports are commonly augmented by means for individual supply of cold and fresh air. This feature provides considerable comfort to passengers who are given to air sickness or discomfort in travelling. The system consists of either an individual scoop or a branch line from the main cold-air intake, and inlets at every seat or station.

The design of such a system entails several problems. The inlets must be easily adjusted by the passengers and provide the desired cold air stream in any direction and amount without causing draft or other discomforts to near-by passengers. Furthermore, opening or closing of a number of inlets should not decrease or increase the flow through other inlets. Finally, the ducting to the inlets must not interfere with the artistic scheme in commercial airliners.

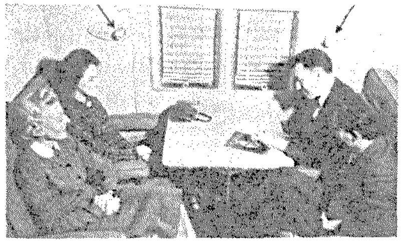

Fig. 32

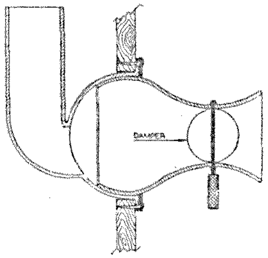

Fig. 33

Figure 32 shows a typical installation of individual inlets, consisting of a small tube which is closed at the end and provided with a hole in the side for the escape of air. The air quantity is adjusted by telescoping the tube into or out of another tube located behind the fabric. Direction of air flow is adjusted by turning the tube. Another design, also permitting easy adjustment of the amount and direction of air flow is shown in Fig. 33.

The maximum air quantity per inlet should be about 5 cfm. If the plane operates in cold climates, it is advisable to provide for some pre-heating of this air; otherwise, too much flow of air at very low temperatures might so cool the area which it serves that it will cause discomfort not only to other passengers but to the user himself. Design of this system for minimum noise requires the utmost attention.

The connecting duct work should, preferably, consist of rectangular, flexible hose from aluminum or fabric which can be formed to the contours of the wall and be made to fit between the skin and cabin fabric.

The main supply duct for the individual stations should not be tapered toward the end of the cabin as is sometimes done. This would assist in unreasonable flow changes with every change in the number of open or closed inlets which can be avoided by making the duct somewhat larger than required for maximum air flow through it and keeping its cross section constant.

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[1] F. C. Houghten, Carl Gutberlet and Edward Witkowski, "Draft Temperatures and Velocities in Relation to Skin Temperature and Feeling of Warmth," *A.S.H.V.E. Transactions,* Vol. 44, 1938.

[2] Society of Automotive Engineers, *Aeronautical Recommended Practices,* ARP 85.

X

CALCULATION OF VENTILATING SYSTEMS

1.0 INTRODUCTION

In the previous chapter, ventilating systems were compared to electric circuits. This analogy applies, in particular, to some of their fundamental laws. In the case of an electric circuit, for instance, the electromotive force or voltage equals the product of the resistance in the circuit in ohms, and of the rate of current flow in amperes. This relationship is called Ohm's Law and is expressed as:

$$E = R \times I$$

In a ventilating system, P, the horsepower required to move a given amount of air through it, is analogous to the electromotive force; the resistance to the air flow results in a pressure drop h, which is expressed in inches of the equivalent height of a water column; and q is the air flow in cfm. The relationship between P, h and q is:

$$P = h \times q \times c \tag{1}$$

in which c is a constant.

In other words, the calculation of ventilating systems uses a basic law which, in some respects, is similar to the Ohm's Law of electricity and permits the calculation of the horsepower required to circulate a given quantity of air against a given backpressure. By the same token, if the horsepower in a given column of moving air is known, it is possible to calculate the maximum permissible back pressure for this rate of air flow.

In designing ventilating systems for aircraft, the air flow or cfm required for a particular purpose is usually established beforehand. Thus, it is known how many cfm are needed for the ventilation of a cabin, anti-frosting of a windshield or anti-icing of a wing. The methods for calculating these quantities are given elsewhere in the text.

The following outline can, therefore, be confined to a discussion of pressures and pressure drops affecting the design of airplane ventilation.

2.0 CALCULATION OF AIR PRESSURES

As a plane moves through the air at high speed, the impact of the air exerts a considerable pressure against those surfaces of the plane's structure which face in the direction of flight. If a hole is cut into the nose or the leading edge of a wing so that the plane of the hole is perpendicular to the air stream, the velocity head or pressure developed during flight drives a certain amount of air into the hole and through attached ducting. This pressure is called *ram* and being made use of in the great majority of ventilating systems on aircraft.

2.1 RAM exerted against a flat plate, perpendicular to the direction of flight, is:

$$V = 1096.5\sqrt{h_v/d} \tag{2}$$

in which: V is the true air speed of the airplane, in fpm; 1096.5 a constant; h_v the ram or velocity head in inches of water; and d the density of the air in lb/cu ft. For dry air at standard conditions (70° and 29.921" Hg barometer), $d = 0.075$ lb/cu ft. Substituting this value in equation (2) yields:

$$V = 4005\sqrt{h_v} \tag{3}$$

In most cases, it will suffice to use this simplified formula since slight changes in atmospheric conditions will not greatly affect the value of h_v. On the other hand, the density was assumed for sea-level conditions while an airplane may fly at an altitude of 35,000 feet at which the density of the air is only about one third of that at sea level. The question arises as to how this will affect the ram.

It so happens that, for constant horespower output of the airplane engine, the ram is unaffected by altitude. This is explained by the fact that, with decreased air resistance at altitude, the speed of the plane increases correspondingly. Equilibrium is established as the resistance of the thin air at higher speed equals that of the denser air at lower speeds. Consequently, the ratio of the velocities equals the square root of the inverse ratio of air densities or:

$$V_a = V_s\sqrt{d_s/d_a} \tag{4}$$

in which the suffixes a and s denote altitude and sea level, respectively.

For this reason, the ram can be calculated for sea-level conditions, no matter what the service ceiling of the airplane is, as long as the power output of the engines remains constant. The curve shown in Fig. 33-A furnishes the ram pressures under this condition, for various air speeds at sea level.

Normally, a plane will cruise at about 60% of rated power so that this curve may be used in practically all cases. If, however, the ram pressure must be found for different engine performance at altitude, it is necessary to use formula (2) and insert the correct, true air speed and density at that particular altitude.

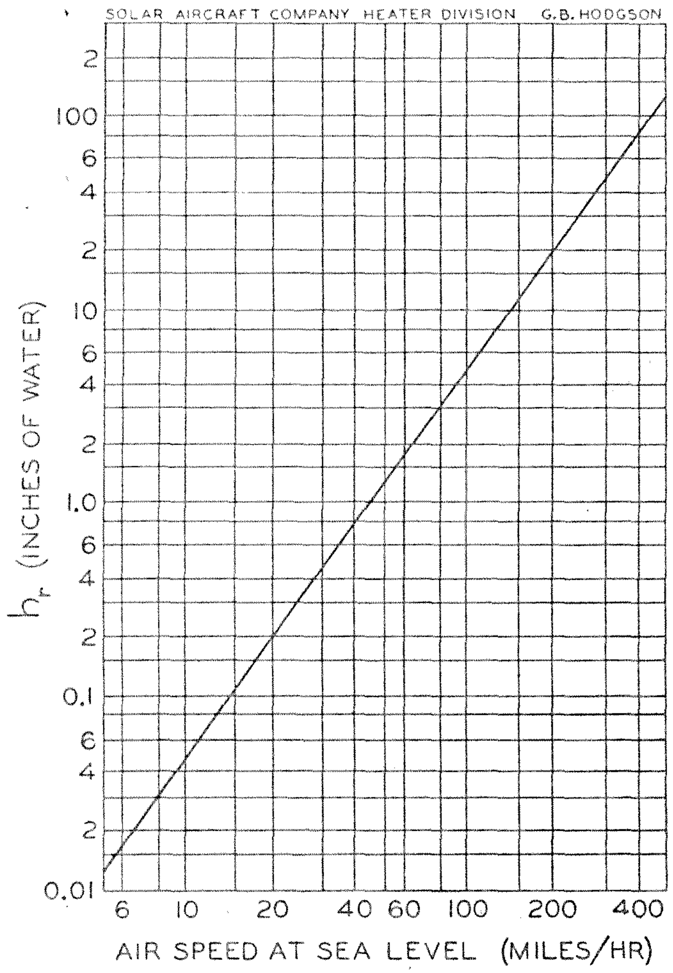

Fig. 33-A

2.2 Blower. Sometimes, it is not possible or feasible to ram in air through a scoop. This is the case if there is no ram available such as in ground ventilation; or if there is insufficient ram such as for the supply of combustion air in some internal combustion heaters; or the drag induced by a scoop of sufficient size must be avoided.

In such instances, it becomes necessary to use a fan or blower. The power required to drive this blower depends on the air quantity which it must supply and the backpressure in the system. In elaborating on formula (1), the following equation is derived:

$$P = \frac{k \times q \times h}{33{,}000 \times e} \qquad (5)$$

in which: P is the required horsepower; $k = 5.2$; q the air flow in cfm; h the pressure head in inches H_2O; 33,000 a conversion factor; and e the efficiency of the fan. For a normal fan, $e = 0.5$ while, for the Sirocco type, e may be as high as 0.65. Since it is advisable to provide a conservative margin, e shall be assumed as about 0.5 and, substituting in equation (5):

$$P \text{ (in h.p.)} = 3 \times 10^{-4} \times q \times h \qquad (6)$$

If the constant 3×10^{-4} is substituted by the letter c, equation (6) is again reduced to formula (1).

Normally, blowers or fans for air supply on aircraft are driven by electric motors. Since 1 kilowatt = 1.341 hp, the electric power required to drive a blower is:

$$P \text{ (in watts)} = 0.224 \times q \times h \qquad (7)$$

Assuming, for instance, that a blower must supply 25 cfm of combustion air against a backpressure of 6″ H_2O, the wattage of the motor required to operate this blower must be:

$$P = 0.224 \times 25 \times 6 = 33.6 \text{ watts}$$

Calculation by means of these formulas is, of course, only approximate but close enough for most applications.

3.0 Calculation of Pressure Drops

The pressure drop in a ventilating system is caused by two factors, namely the dynamic losses incurred by change in the direction or velocity of the air flow such as in bends, dampers, outlets and the like; and by the friction losses which are due to friction of the various air layers among themselves and against the walls of the duct.

The *back pressure* of a duct or any other component of a ventilating system is the drop in pressure or velocity head an air stream suffers while passing through such a component. This may also be termed the *resistance to air flow*. However, the designation *pressure drop* is the most common as it better conveys the importance of the fact that none of these expressions, by itself, has any meaning. Thus, in stating that the pressure drop through a ducting system is 4″ H_2O, it is also necessary to give the mass flow rate of the air or the pounds of air flowing through a unit area in unit time which create this pressure drop. Similarly, the amperes flowing through an electric circuit are meaningless unless the voltage is given which produced this current flow.

The relationship between pressure drop and air flow is quite involved. It depends not only on the mass flow rate but also the shape of the air conductor, the roughness of its surface and the air density. For instance, the pressure drop through a circular duct is established by the following equation:

$$\Delta P = \frac{fG^2L}{2g^2\rho D} \qquad (8)$$

in which:

ΔP = Pressure drop, in lb/ft^2
f = Friction factor, non-dimensional
G = Mass flow rate, lb/sec/sq ft
L = Duct length, ft
g = Acceleration constant, 32.16 ft/sec^2
ρ = Mass density, slugs/ft^3
D = Inside diameter of duct, ft

The friction factor f is a function of the ratio of k—the height of roughness on the inside surface of a duct—to the duct diameter, and the so-called Reynolds number R_e which is defined as:

$$R_e = \frac{G \times D}{\mu} \qquad (9)$$

in which μ = Absolute viscosity, lb/sec/ft

Similar equations are given for square and rectangular ducts as well as other shapes. Obviously, calculations by means of these formulas

are not only complicated and time-consuming but also intended for an accuracy which, in most cases, is not required. Friction factor and other data usually must be assumed and may vary considerably within each installation. In addition, it is necessary to allow for sufficient margins in order to compensate for unforeseen contingencies.

For this reason, the author in cooperation with G. B. Hodgson, staff engineer at Solar Aircraft Company, worked out a method which simplifies these calculations at the expense of some accuracy. However, the results thus obtained are usually close enough. This method is based on establishing the pressure drop through a particular air conductor for standard conditions and unit dimensions, and multiplying it by factors, given in graphs, for different conditions and dimensions.

The basic pressure drop has been termed the *Specific Resistance* of an air conductor and designated by the symbol R_s. The fundamental formula for the relationship between pressure drop and specific resistance is then:

$$\Delta P = R_s \times d_s/d_a \times \tau \qquad (10)$$

in which:

ΔP = Pressure drop, inches H_2O
R_s = Specific resistance of an air conductor, inches H_2O
d_s/d_a = Correction factor for altitude
τ = Correction factor for temperature.

The significance and use of these factors is described below.

3.1 CORRECTION FOR ALTITUDE. As the airplane rises to higher elevations, the density of the air decreases. Thus, a cubic foot of air, which weighs 0.075 lb at sea level, weighs only 0.0549 lb at 10,000 ft and 0.0343 lb at 25,000 ft. At 35,000 ft, it weighs about one third of its sea-level value.

If it is required to keep the weight of the air flow constant, its volume must be increased as its density decreases. For instance, 7.5 lb of air per minute are supplied by a flow of 100 cfm at a sea level, but three times that many cubic feet or 300 cfm are needed to supply the same weight of air at 35,000 feet where the density is only one third.

Assuming now, that 100 cfm which flow through a duct at sea level suffer a pressure drop of 2″ H_2O, how is the pressure drop affected, if three times that many cubic feet pass through the duct at 35,000 ft altitude? The weight of the air is the same in both cases but, obviously, the pressure drop must be higher at altitude since so much more volume is squeezed through the duct which, of course, has not changed its size. A study of equation (8) will show that a given pressure drop at sea level will increase approximately in the same proportion as the air density decreases so that the pressure drop at altitude, for constant mass flow, is:

$$\Delta P_a = \Delta P_s \times d_s/d_a \qquad (11)$$

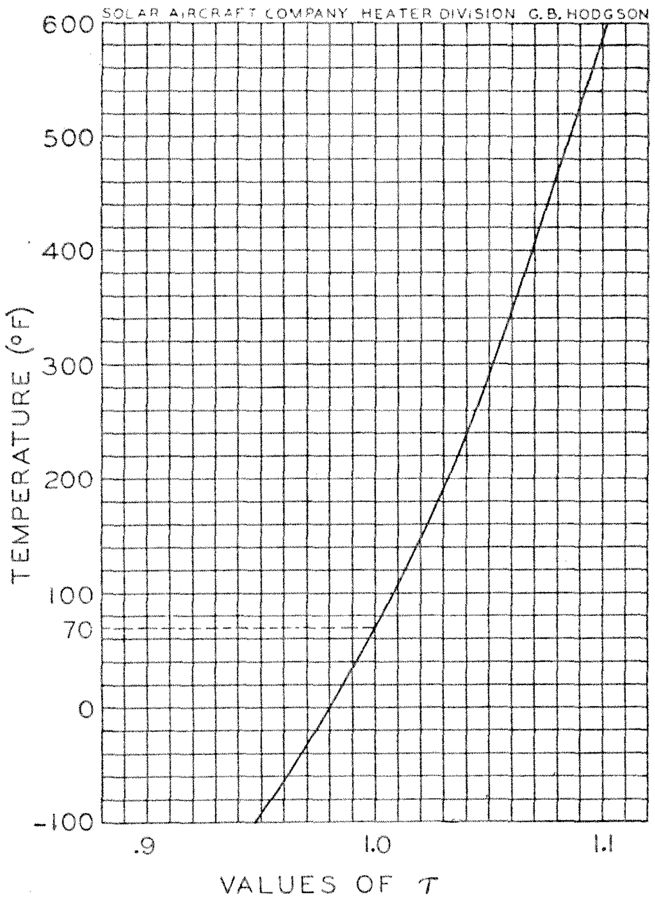

Fig. 33-B

in which: ΔP is the pressure drop, d the air density, and the suffixes a and s again denote altitude and sea level, respectively. Consequently, in order to calculate the increase of sea-level pressure drop for the same mass flow of air at any given altitude, it is merely necessary to multiply ΔP_s by d_s/d_a, the ratio of air density at sea level to that existing at the given altitude. This ratio has been plotted on a graph shown in Fig. 43 where it can be read as a function of the altitude.

3.2 CORRECTION FOR TEMPERATURE. It was mentioned before that R_s is defined for standard conditions, and it has been computed on that basis to obtain the values for the curves which will be discussed shortly. Standard conditions, however, take into account not only those existing at sea-level densities but also a standard temperature. For this reason, it is necessary to multiply R_s by a correction factor, τ, which is based on the value 1.0 for 70°. The corrections required for lower or higher temperatures are given in Fig. 33-B. As can be seen, slight variations in temperature hardly affect this factor so that it can be neglected in a great many cases.

3.3 PRESSURE DROP IN STRAIGHT DUCTS. As a practical example of the use of the specific resistance R_s, it will be shown how to apply it to friction losses in a straight duct. The unit length of the duct shall be 1 ft so that the pressure drop through a length of L ft, at any altitude and temperature, is:

$$\Delta P = R_s \times d_s/d_a \times \tau \times L \qquad (12)$$

At standard conditions, that is at sea level and 70° temperature, d_s/d_a and τ are 1. For one-foot length of duct, the pressure drop then equals the specific resistance, which is in accordance with the latter's definition.

It will be noted that the shape of the duct does not enter into this equation so that it applies to round, square, rectangular and annular ducts. This is explained by the fact that the curves provided in Fig. 33-C for finding the specific resistance at various mass flow rates are based on the hydraulic diameter of the duct.

The hydraulic diameter, D_h, is established by the formula:

$$D_h = \frac{4A}{P} \qquad (13)$$

in which:

D_h = Hydraulic diameter, in.
A = Area of the duct, sq in.
P = Wetted perimeter, in.

The *wetted perimeter* of a duct is the curve which, in a cross-sectional view of the duct, encloses the flow area and is touched or "wetted" by the air flow. For instance, in a round duct, that curve is the periphery and its length $2\pi r$. In a square or rectangular duct, the air obviously touches all four sides so that the perimeter is the sum of the side-lengths. Thus, if a duct is 6″ wide and 3″ high, its wetted perimeter is 18″. In an annular duct, the perimeter is the sum of the outer and inner peripheries.

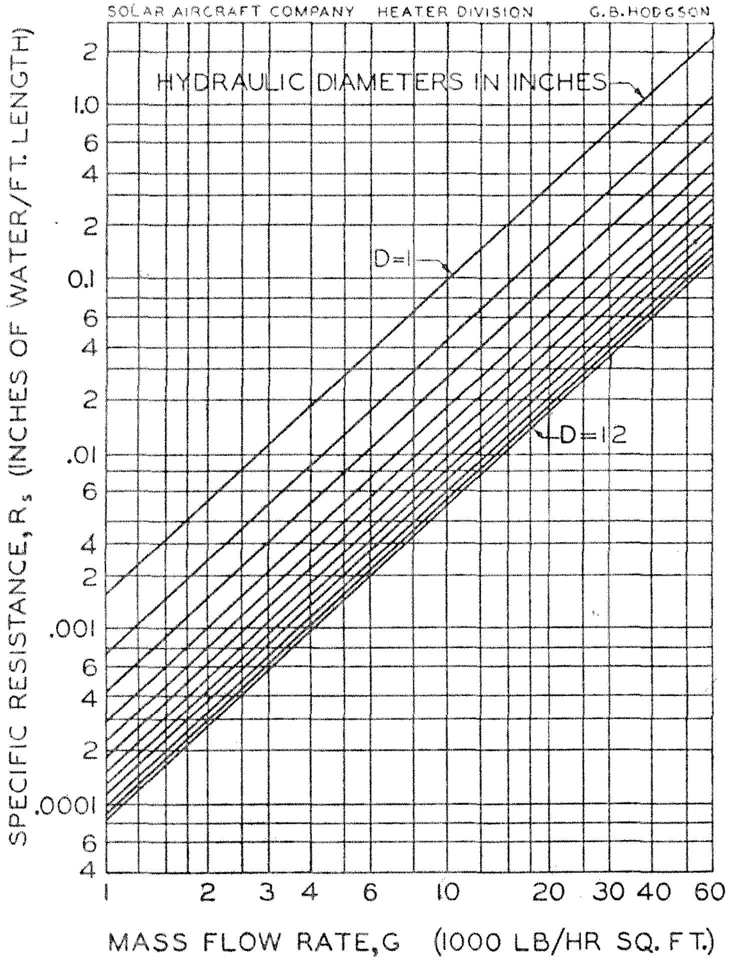

Fig. 33-C

Calculating, for instance, the hydraulic diameter of a round duct, it is found that:

$$D_h = \frac{4A}{P} = \frac{4 \times \pi \times r^2}{2\pi r} = 2r$$

In other words, the hydraulic diameter of a round duct is equal to its regular diameter.

If the hydraulic diameter of a straight duct has been calculated, its specific resistance R_s at any particular mass flow rate can be found from the curves in Fig. 33-C. This value is then inserted into equation (12) and such corrections added for altitude or temperature as are necessary.

It should be mentioned that these curves are for isothermal flow, that is, the air temperature throughout the length of the duct is assumed to be constant. If there is a difference between air inlet and outlet temperatures, it should suffice normally to establish the average temperature and base the factor τ on that.

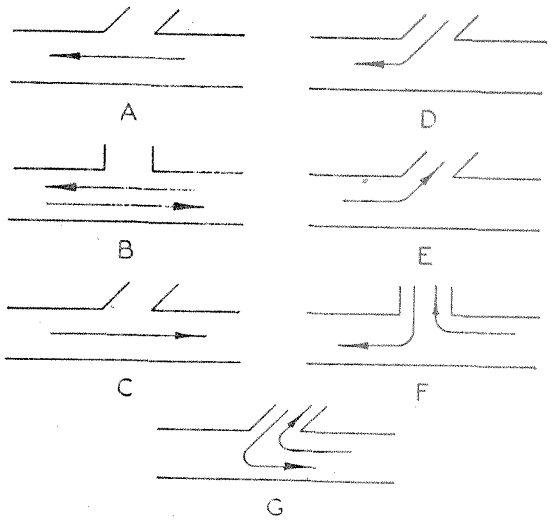

Fig. 33-D

3.4 PRESSURE DROP OF BRANCH DUCT CONNECTIONS. If air flows from one duct into another, its direction and velocity are changed, resulting in a pressure drop. This drop depends on the mass flow rate, the angle at which the air enters the other duct and, if air should be flowing in this other duct, the latter's direction. These possibilities are illustrated in Fig. 33-D. The corresponding specific resistances at various mass flow rates are given by the curves in Fig. 33-E. The pressure drop at any altitude, caused by a branch connection, is then found as:

$$\Delta P = R_s \times d_s/d_a \qquad (14)$$

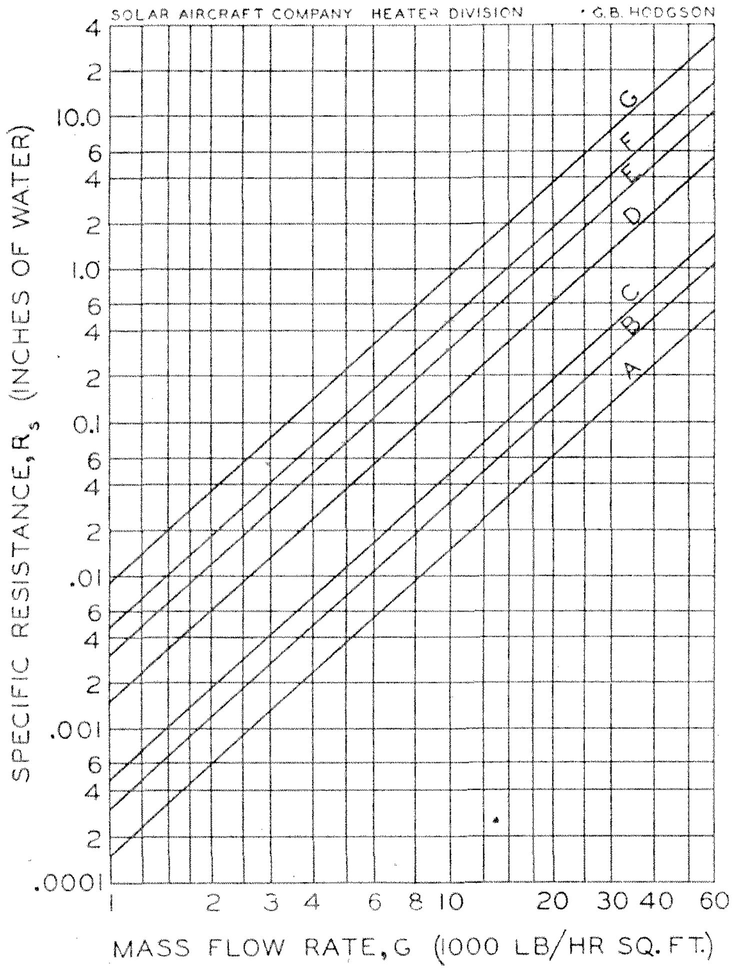

Fig. 33-E

Since the friction factor does not enter into this calculation, no correction for temperature is necessary.

3.5 PRESSURE DROP THROUGH ROUND ELBOWS. Pressure drops through round elbows are found by means of equation (14). In Fig. 33-F, their specific resistances at different mass flow rates are plotted for a variety of radius ratios, which are defined as the ratio of the bend radius to the diameter of the duct, as shown in Sketch *A* of Fig. 33-G.

It should be noted that the values for R_s, found in the curves, must be multiplied by ten for radius ratios from 0.5 to 2, inclusive.

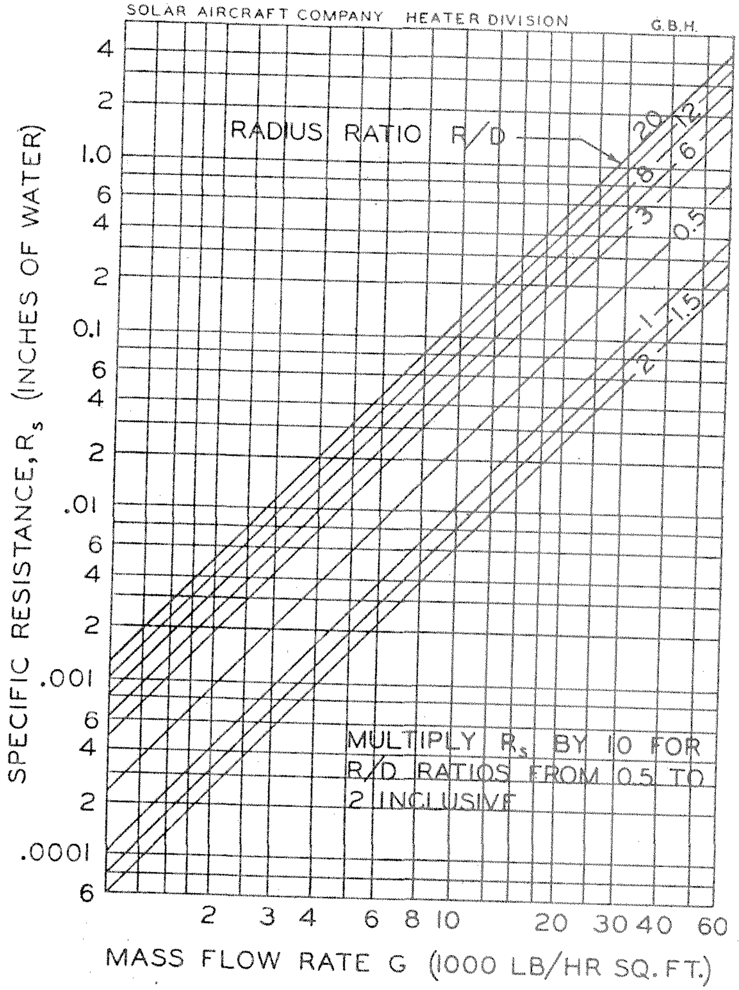

Fig. 33-F

3.6 PRESSURE DROP THROUGH SQUARE ELBOWS. The specific resistances of square elbows at various mass flow rates and radius ratios are given by the curves in Fig. 33-H. The radius ratio, in this case, is the ratio of the bend radius to the length of the side of the square, as shown in Sketch *B* of Fig. 33-G. It is necessary to multiply R_s by 10 for radius ratios from 0 to 3 inclusive.

R_s is inserted into equation (14) to find the pressure drop at any altitude.

3.7 PRESSURE DROP THROUGH DAMPERS. The pressure drop through a damper depends, in addition to the factors mentioned above, on the damper setting or the angle between the damper and the direction of air flow as illustrated in Sketch *D* of Fig. 33-G.

Specific resistances of dampers at various mass flow rates and damper settings are given by the curves in Fig. 33-I. ΔP for different altitudes is found by means of formula (14).

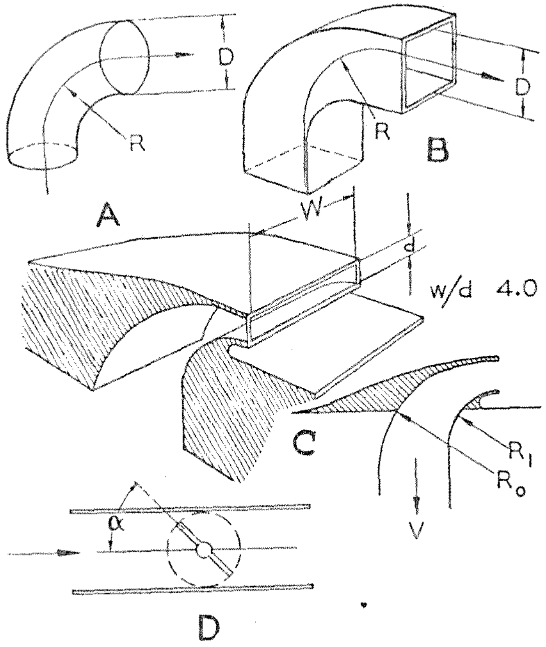

Fig. 33-G

3.8 PRESSURE DROP THROUGH SCOOP. The pressure drop which an air stream suffers when passing through a scoop is somewhat more difficult to calculate since the scoop area is, often, not uniform. In the scoop shown in Sketch *C* of Fig. 33-G, the area expands, thus forming a venturi. The purpose of this construction is to obtain high static pressure at low velocity although, at the mouth of the scoop, the static pressure is low and the velocity high. Such a scoop construction is, therefore, ideally suited for aircraft installations, particularly, since this permits a smaller opening for the scoop in the skin of the plane and, consequently, induces less drag.

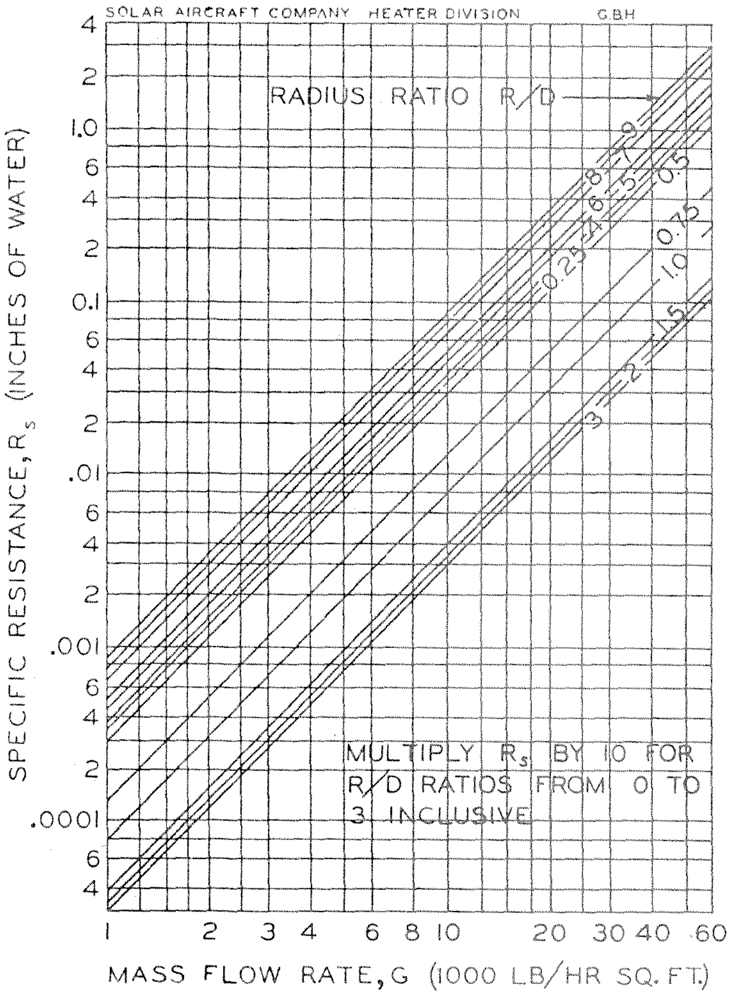

Fig. 33-H

There is, however, a certain pressure loss connected with this construction which is calculated in the following manner:

$$\Delta P = R_s \times d_s/d_a \times \Psi \tag{15}$$

in which Ψ is a factor depending on the aspect ratio w/d, which is usually 4.0 (see Sketch *C* in Fig. 33-G), and the ratio of the outer bend radius R_o to the inner one, R_i. Values of Ψ for various aspect ratios and values of R_o/R_i are given in Fig. 33-J.

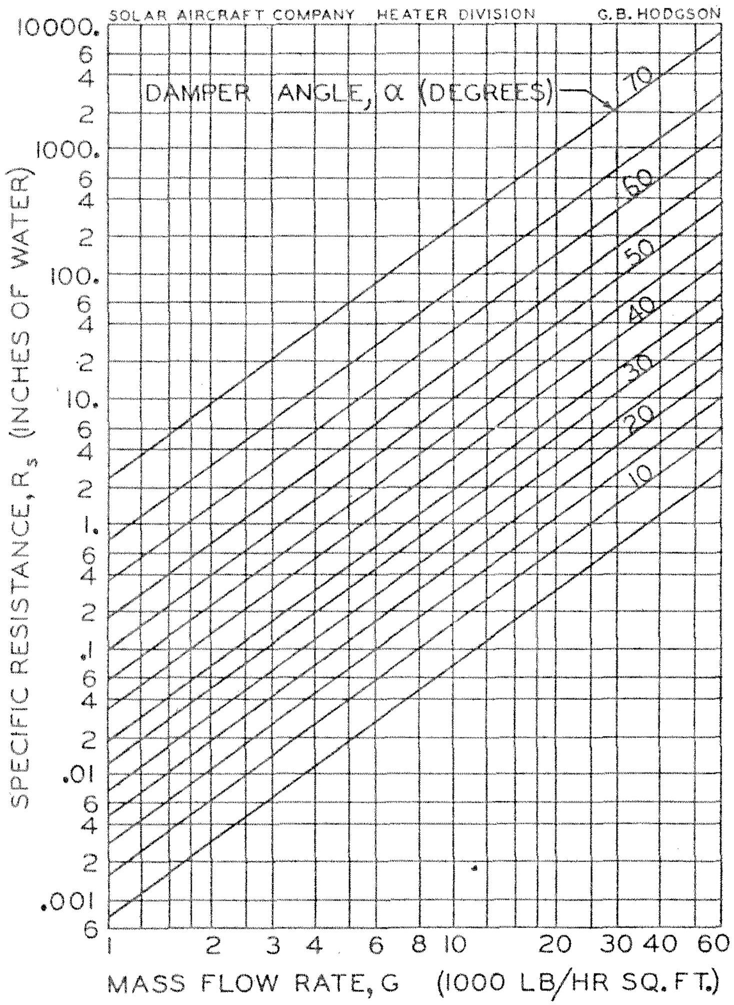

Fig. 33-I

The specific resistance of a scoop depends on the ratio of the smaller scoop area to the larger one, or A_1/A_2. Values for R_s at different area ratios and mass flow rates are plotted in Fig. 33-K.

The values found for Ψ and R_s are inserted into equation (15) which then yields the pressure drop at any altitude.

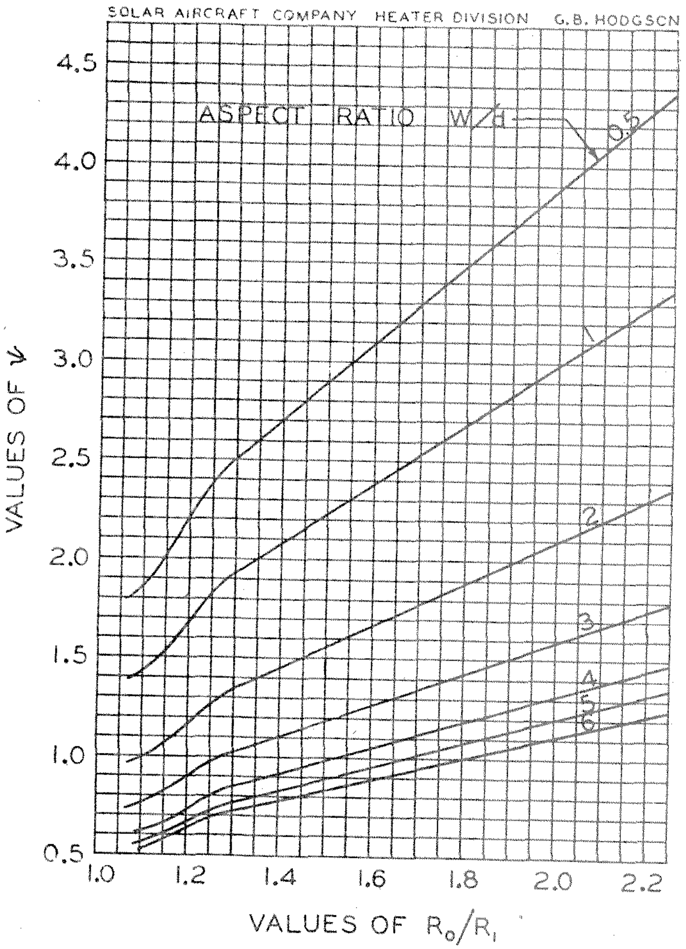

Fig. 33-J

3.9 PRESSURE DROP THROUGH MISCELLANEOUS RESISTANCES. A ventilating system on an airplane as well as on the ground contains a great variety of components which add to the total pressure drop through the system. Such components may be deflecting vanes, diffusers of manifold types, transitions, heaters, radiators, gate valves, nozzles, grilles and many others too numerous to mention. Since, in addition, sizes, shapes and constructions vary considerably, it is impossible to discuss even a small fraction of such devices in this space. Frequently, the manufacturer will supply the desired air-flow data. Added information can also be found in specialized publications such as the *SAE Aeronautical Information Report No. 2*, from which many of the data for the calculation of the curves accompanying this chapter were obtained, and other sources some of which are listed among the references below.

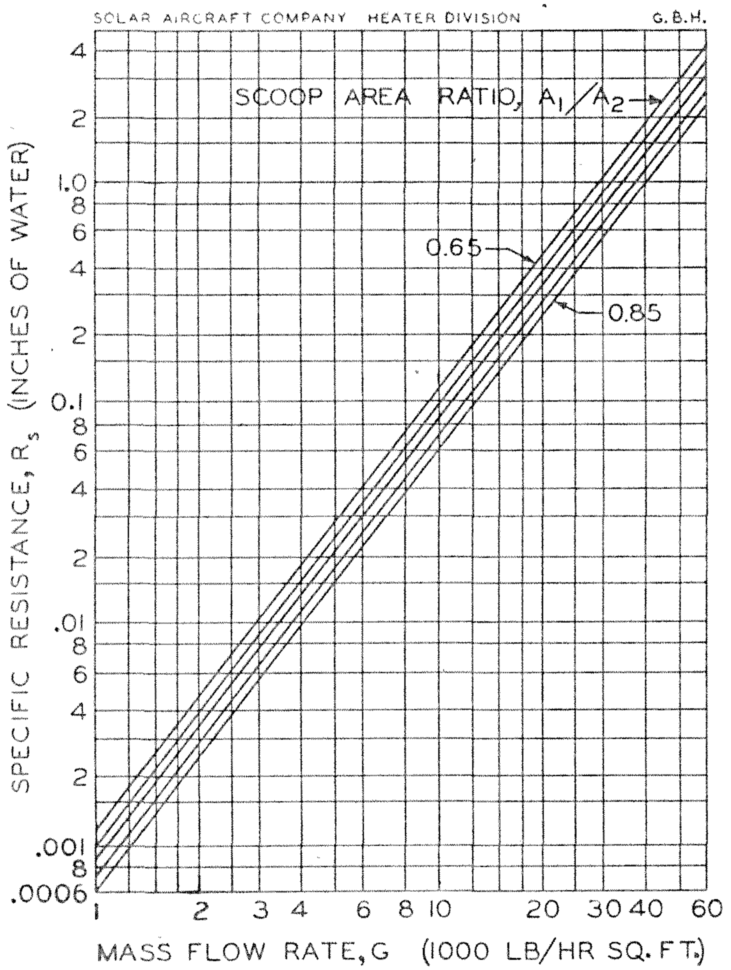

Fig. 33-K

There is, however, a simplified method of establishing R_s for any component part of a ventilating system. If the value $\frac{G^2}{2g^2\rho}$ in equation (8) is designated as λ, the specific resistance of any component causing a dynamic pressure loss can be expressed as:

$$R_s = \lambda \times k \tag{16}$$

in which k is a constant for that particular component.

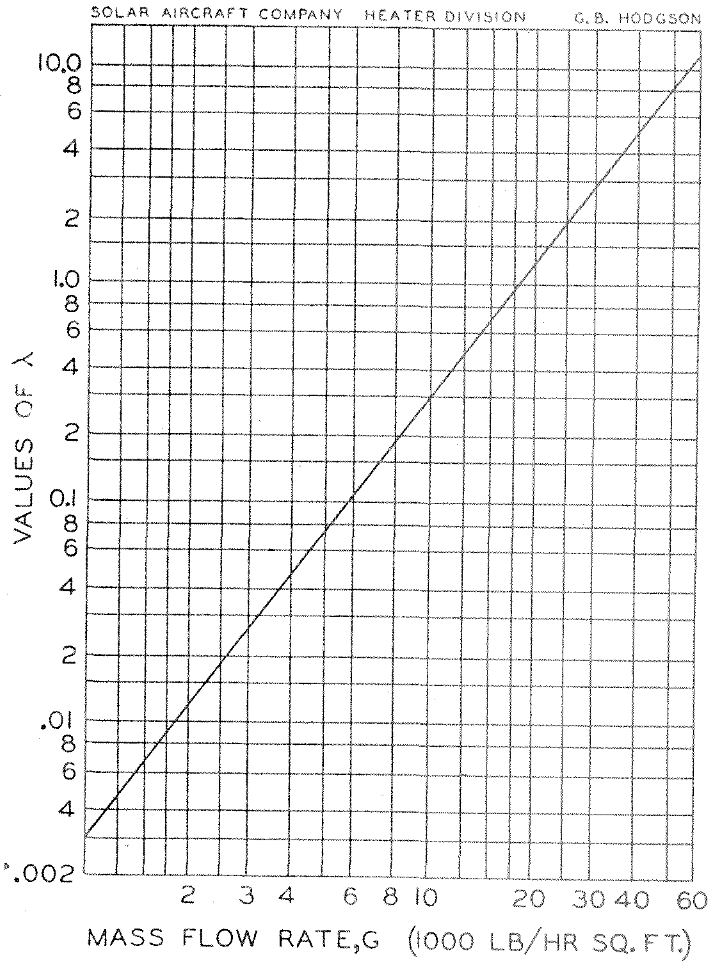

Fig. 33-L

If k can be found empirically, as is often possible, the calculation of R_s is not difficult. Assuming, for instance, that it is desired to find R_s for an airplane heater, ducts are connected to it and air passed through the system. Measurements are then taken of the air pressures at the inlet and outlet of the heater. Their difference represents the pressure drop through the unit. Next, the air flow rate is measured at which this pressure drop occurred. Inserting the pressure drop thus established into equation (16) as R_s and finding λ in Fig. 33-L as a function of the measured mass flow rate, yields the value for k.

R_s can now be calculated for all other mass-flow rates since k remains constant. Using equation (14) again, the pressure drop through the heater can be found for all conditions of air flow and altitude.

One factor which must be observed in using k is that the physical dimensions of the unit for which k has been measured may not be changed. For example, if k has been found for a gate valve at a particular setting, any change in the setting of the valve will affect k so that it must be established separately for a number of intermediate settings from full open to full closed, unless the valve is to be used only fully closed and at one other, specific setting. This fact will not be overlooked, if it is realized that any change in the setting of a valve, louvre or shutter will entirely change the characteristics of this part, and, with it, its effect on air flow.

4.0 CALCULATION OF AREAS

The flow area is a function of the air quantity and velocity. The equation for calculating either one of them, if the other two are given, is:

$$q = A \times V \tag{17}$$

in which:

q = Air quantity, cfm
A = Cross-sectional flow area, ft^2
V = Velocity, fmp

4.1 AREA OF DUCTS. In calculating the size of ducts, the air quantity which must be conveyed through a particular duct is usually given. For instance, if a duct is to be branched off from the main warm-air duct to the windshield of an airplane for anti-frosting purposes, the heat requirements of this installation must be calculated first. Once these requirements are known, the air quantity needed to supply the calculated amount of heat at the desired temperature is automatically established.

Since a duct is merely the means for carrying air from one point to the other, the quantity of the air is determined solely by its end use, which may be ventilating, heating or cooling. Consequently, it is computed by considerations other than duct sizes.

There is, however, one exception which applies to airplane installations. If the duct sizes required to carry a calculated amount of air should prove to be unreasonably large or cannot be incorporated into the structure of the fuselage or wings, it is sometimes necessary to decrease the quantity either by increasing the air temperature or, in some other manner, cutting down on the air requirements.

A point which is frequently overlooked in this respect is the increase in air volume at altitude. If, for instance, the air requirement has been found at 7.5 lb/min, the equivalent volume at sea level is 100 cfm. Assuming now that a duct has been designed for passing this volume at a velocity of 2000 fpm and a pressure loss of 4″, conditions at, say, 35,000 ft altitude would become quite difficult. At about one third the density of air, constant mass flow would require 300 cfm which then pass through the duct at the excessive velocity of 6000 fpm and suffer a pressure loss of 12″. Apart from all other disadvantages, the ram may not be large enough to supply the required volume against so high a backpressure and, as a result, the mass flow decreases. For this reason, installations depending on constant mass flow must be calculated on the basis of air volumes at the service ceiling of the airplane.

Once the value of the product $A \times V$ is given, the establishment of either one is, normally, a matter of choice. A high velocity is not desirable from the standpoint of noise. In addition, air discharged into the cabin at high velocities causes harmful and disagreeable drafts. As a rule, air velocities in ducts should not exceed 1200 fpm, if the ducts are within a soundproofed cabin, and be below 3000 fpm in ducts outside of the cabin. With air quantity and velocity known, the area of the duct can be calculated by equation (17).

On the other hand, the calculated duct size may be impossible to provide due to space limitations, or the ensuing weight may be considered too high. In this case, it is necessary to permit an increase in air speed unless it is possible to get along with smaller quantities.

In calculating a main duct from which smaller ducts branch off at various points, it is common practice to decrease its size after each take-off in accordance with the decrease in air quantity which it has to carry from that point on. However, if space and weight permit, it is frequently advisable to leave the size of the main duct unchanged. In this case, the duct acts as a plenum chamber or buffer which not only tends to counteract pulsations in the air flow but also serves as an acoustical capacity, decreasing the noise level of the ventilating system. This scheme is of particular usefulness in systems where the flow through the branch ducts may vary considerably as, for instance, in the individual cold air supply systems of airliners. As one or more of the air nozzles which are provided for each passenger are opened or closed, strong pulsations may result which can be minimized by a plenum system of ducting.

4.2 CALCULATION OF SCOOPS. The velocity head available at the mouth of a scoop is, according to equation (2):

$$V = 1096.5\sqrt{h_v/d}$$

Since V, the true air speed of the plane, is given, the equation is solved for h_v and the ram is then:

$$h_v = \left(\frac{V}{1096.5}\right)^2 \times d$$

This, however, is not the pressure which drives the air through the ducting system but rather the pressure exerted against a flat plate, perpendicular to the direction of flight, as explained before.

If the plate is removed and the air stream permitted to enter an opening, such as a scoop, in the structure of the plane, the pressure which tends to drive this air stream into the scoop and through the attached ventilating system is opposed by the backpressure within this system. In other words, the movement of the air through the system is impeded by frictional and other resistances which act in a direction opposite to that of the ram. Consequently, the resistance or back pressure of the system to a given air flow must be deducted from the available ram, and the remaining difference is then the pressure which produces the desired air flow.

This is best illustrated by the following example: Assuming that the air speed of a plane at sea level is 150 mph or 13,200 fpm, then the velocity head, in inches of water, is, according to the simplified equation (3):

$$h_v = \left(\frac{13,200}{4,005}\right)^2 = 10.89'' \text{ H}_2\text{O}$$

The pressure losses in this particular system are caused by a number of resistances which shall have been calculated on the basis of assumed air flow as follows:

Air intake and screen:	= 2.5″
Rain eliminator and trap:	= 1.5″
Exhaust-gas heat exchanger:	= 2.5″
Supply ducts and dampers:	= 0.63″
Inlets in cabin:	= 0.05″
Positive pressure in cabin:	= 0.75″
Total Pressure loss	= 7.93″ H_2O

Deducting this value from the velocity head, 10.89, gives an available pressure at the intake of $h = 2.96'' \text{ H}_2\text{O}$.

This pressure determines the speed of the air entering the scoop, namely:

$$V = 4005\sqrt{h} = 4005\sqrt{2.96} = 6,890 \text{ fpm}$$

If it is further assumed that the required air quantity is 1500 cfm, the intake area of the scoop can be found by means of equation (17) and:

$$A = Q/V = \frac{1500}{6890} = 0.218 \text{ sq ft}$$

In order to compensate for intake losses of about 25%, this value is increased to 0.3 sq ft, so that:

Area of intake scoop = 43.2 sq in.

The dimensions of a scoop of this area are then established in accordance with structural requirements.

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[5] Herman J. Stoever, *Applied Heat Transmission,* New York, 1941.

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[7] Charles A. Mobley, "Essentials of Airplane Duct Design," *Aero Digest,* January 15, 1944.

XI

SELECTION OF AIR SUPPLY

There is a sufficient variety of means for air supply and its distribution to furnish a satisfactory combination for every conceivable purpose.

Although it was shown that no rigid rules can be established for the selection of the best suitable combinations which would apply under all or even most conditions, the basic characteristics of the three comfortization types of aircraft permit common methods of approach which will be analyzed in the following.

1.0 Air Supply for Cockpit-type Aircraft

Turning first to planes of the cockpit type, it is unwise for the comfortization engineer to brush the problems of air supply aside in the conviction that so much air is streaming into and through the cockpit that there is too much rather than too little air.

The cockpit must be so designed that no harmful gases, fumes and odors can enter it under normal conditions of flight and combat. If the hood is open, the resulting drafts warrant close attention so that the suction effect of the air stream will neither cause unreasonable under-pressures within the cockpit nor will the ensuing draft result in serious discomfort to the exposed parts of the flyer's body (Fig. 34).

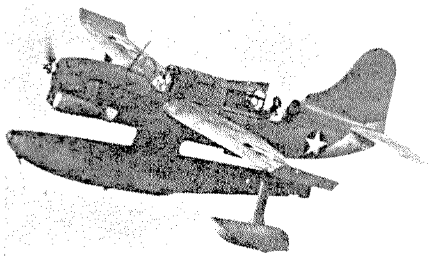

Fig. 34

If the hood is closed, it must be ascertained beyond doubt whether sufficient air leaks into the cockpit to conform with the requirement of 135 pounds of fresh air per hour and per person. Since it is difficult, if not impossible, to calculate accurately the amount of air infiltration into the closed cockpit, it is essential to check the air supply in flight, and at the highest ceiling the plane is expected to fly without the use of oxygen equipment.

While in most planes of the cockpit type enough air will be supplied by natural infiltration, such a method, simple as it is, has many disadvantages. Turbulences caused around the cracks through which the air is expected to infiltrate increase the drag of the plane. Proper calculation of the air supply is practically impossible. Furthermore, it is very difficult to check or direct the drafts, keep rain out of the cockpit, etc. It is much better to provide an air-supply scoop and complete, airtight closing of the hood during flight, with a foul-air spill so designed and located as to prevent drafts near the pilot or other occupants, and to build up a slightly positive pressure within the cockpit.

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Apart from other advantages, such as decreasing the noise level in the cockpit and facilitating heat supply, this method permits an accurate calculation of the air weight supplied at all altitudes. Dive-bombers are provided with scoops of this type to provide a blast of cold air for the pilot's face which aids in overcoming the effects and after-effects of black-outs during dive-bombing. Scoops for these purposes are, preferably, located in the leading edge of the wing and will add less drag than a semitight hood.

Since the ram effect of the scooped-in air tends to compress the air within the cockpit, somewhat greater altitudes can be obtained without the use of oxygen in a sealed cockpit than in one that is open or subject to uncontrolled infiltration and exfiltration.

1.1 supercharging of cockpit-type planes. If altitudes have to be attained at which not only the oxygen content of the air but also its pressure is too low for minimum physical requirements, complete sealing of the cockpit and air supply by means of a blower are necessary. The weight and electric current consumption of the blower are high and an undesirable burden to the light and fast-flying, high-altitude planes of the cockpit type.

However, the fastest and lightest plane is useless, if no human being can operate it at the design ceiling. Therefore, supercharging with all its disadvantages must be resorted to at very high altitudes and, if possible, even at altitudes where oxygen equipment alone is usually sufficient. It must be realized that insufficient air pressure and rapid pressure changes can be just as harmful, particularly over a period of time, as low oxygen supply. This, incidentally, is another strong point for the airtight cockpit.

The previously broached problem of what happens when a supercharged, military plane is damaged by enemy fire warrants the most serious consideration. It is, of course, impossible to so protect all of the essential components of a warplane that, under no circumstances, will damage result in putting the plane out of action.

The designs of the plane manufacturers and the specifications of Army and Navy can merely provide for the utmost in safety and guarding of vital elements of the plane against enemy fire which is still compatible with the required functions of such an airplane. An interceptor designed to fly at such speeds and altitudes as to outfly enemy bombers or attack planes cannot very well be provided with one-inch armor around cockpit, fuselage or engine nacelles. There can be only a reasonable compromise between suitability for a definite purpose, and protection for the pilot and important components of his ship.

This holds equally true for air supply. A shell or fragment shattering the oxygen bottle or tearing the supply hose at high altitude may be just as fatal as a shell which destroys the propeller or hits the pilot. Therefore, air-supply equipment for high altitudes warrants reasonable precautions against extreme vulnerability. In the case of a supercharged plane—no matter how small or big—the supercharger must be so dimensioned as to provide for a margin of excess capacity which will render small holes, cracks, etc. reasonably harmless. As an ultimate precautionary measure, subdivision of the cabin into various airtight compartments may prove to be necessary. However, if the plane is so badly damaged that the supercharger can no longer provide the minimum requirements of oxygen or pressure, the plane is probably equally disabled in other respects and must be abandoned.

A general analysis of the best suitable means of air supply on high-altitude cockpit aircraft, will reveal that individual and low-pressure oxygen supply is usually preferable to supercharging for military planes, unless extremely high service ceilings or particularly great pressure changes make the latter mandatory. Nonmilitary cockpit planes which operate regularly above 15,000 feet should be supercharged whenever feasible. Otherwise, individual, high-pressure oxygen supply should be provided.

2.0 AIR SUPPLY FOR CABIN-TYPE AIRCRAFT

2.1 MILITARY. The selection of air supply for the conventional military plane of the cabin type is not easy. These planes—usually two-engine craft with from three to six crew members—are provided with numerous openings for the disposition of military equipment such as guns, cameras, sights etc. Some planes of this type have large gun blisters which are opened during combat.

Obviously, the uncontrollable infiltration of air is so strong that, under most circumstances, it will suffice to supply all air needs for breathing at medium altitudes. Again, considerations of draft, carrying away of foul and malodorous air, smoke, and carbon dioxide or monoxide, and the need for greater air quantities by volume at higher altitudes must be the prime factor in determining whether natural ventilation is sufficient.

Instead of the air requirements of the crew alone, it is necessary to consider the potential requirements of a maximum number of additional passengers who may have to be carried in an emergency. So it is preferable to calculate on the basis of air changes per hour rather than air quantities per person. Due to the altitude requirements, there should be not less than 20 complete air changes per hour which should suffice for all contingencies.

No matter how effective the natural air circulation through the plane is, it is mandatory to provide for auxiliary ventilation for hot weather, an excess number of passengers or such exceptional conditions as may arise for a number of reasons in the course of military operations. The simplest means for auxiliary air supply are ventilation flaps or scoops augmented by spills for better circulation. These devices will usually suffice for flights up to medium altitudes and beyond that, if oxygen equipment is used.

Considerably more desirable—particularly from the standpoint of efficient air distribution and heat supply—is central air supply by means of a scoop in the leading edge of the wing. In an installation of this type, the air may be distributed either through an overhead duct and ceiling diffusers, or through common floor ducts and branches of flexible aluminum hose, terminating in nozzles or similar inlets. The choice, in this case, depends entirely on the method of heat supply with which the ventilating system may have to be combined.

Central air supply is more difficult to install and takes up added weight and space. Therefore, it should be limited to military cabin planes which are rather well insulated and on which the requirements of both air and heat supply are stricter than they are normally for planes of this type.

2.2 AIR SUPPLY FOR MILITARY CABIN PLANES AT HIGH ALTITUDES has caused considerable trouble for comfortization engineers. Portable oxygen equipment is simple but its bulk and weight become a more serious factor than on the cockpit-type plane. On the cabin-type warplane quick motion from one place to another is often of the greatest importance, particularly during combat and in emergencies. The carrying of oxygen equipment impedes such motion and the rapid actions which may be required.

Central oxygen supply, on the other hand, frees the crew members of the need of carrying their equipment around while it compels them to stay within the range of the hose with which they connect their mask to the oxygen-carrying pipe along the wall. Even if the length of this hose is considerable, permitting them a certain freedom of motion, they have to disengage the hose and thus interrupt the oxygen supply, if they move beyond the length of their supply hose. Any delay in the resumption of oxygen supply can be fatal.

Finally, there is the possibility of supercharging the cabin with ensuing problems similar to those analyzed for the cockpit-type plane. Still, for very great altitudes supercharging is most desirable for cabin-type planes, and preferable to the use of portable or central oxygen supply, as long as proper precautions can be taken to cope with all contingencies.

Whether the advantages of supercharging can be fully utilized for this type of military craft during this war, is another question. For the present, oxygen equipment still offers the best solution for high-altitude operation. This equipment should be of the central and low-pressure type, with portable units carried for emergencies.

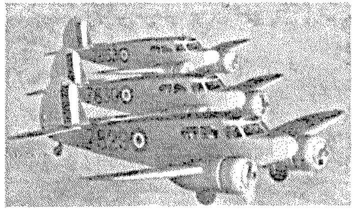


Fig. 35

2.3 NONMILITARY planes of the cabin type may be either small, private craft or medium-sized transports. Considerations of air supply for the former are the same as for the cockpit type, nonmilitary planes, while the latter's requirements are very similar to commercial, compartment-type planes (Fig. 35).

3.0 AIR SUPPLY FOR COMPARTMENT-TYPE AIRCRAFT

3.1 MILITARY. The compartment type includes transports, cargo and ambulance planes, long-range bombers and the like. Fundamentally, military transports are but little different from commercial planes of corresponding size. Usually of long range, medium ceiling and voluminous interior to accommodate a large number of people, they require a considerable amount of comfortization. Efficient air supply is a vital factor, not only on account of the larger number and, often, weakened or sick passengers, but also because of the longer duration of flights, presence of galley and lavatory odors, etc.

Air supply on such planes is almost invariably coupled with the heating system, requiring ducting, air diffusers as described before, or grilles, foul-air outlets and, whenever possible, individual cold-air supply.

Although the requirements of comfort are not nearly as high as they are on a commercial transport, the means and equipment used to meet them are quite similar, necessitating well-planned design. The passengers carried are often unaccustomed to flying and, unlike the crew members, not always selected for their physical qualifications as airborne passengers as are paratroops. Therefore, it is necessary to make certain concessions which, normally, would not be made on a warplane.

While the long-range bomber is also a compartment-type plane, its crew is usually quite small, considering the available space. Nevertheless, these airplanes have often been used for the emergency transportation of numerous passengers and should, therefore, provide sufficient air supply for the maximum possible number of persons they may carry. Accordingly, their air supply should be calculated on the basis of 15 to 20 complete air changes per hour.

Another difference between the military transport and the long-range bomber lies in the fact that the former usually flies at medium altitudes while the latter, in many cases, has service ceilings requiring oxygen equipment or, possibly, even supercharging. The selection of the air supply at high altitudes again hinges on various considerations such as the requirements of the heating system, problems of fuselage design, control of guns in exposed parts of the plane, etc.

Quite generally, it will be found that the oxygen equipment for a large plane will not weigh much less, possibly even more, than supercharging equipment. And portable or central oxygen supply or a combination of both does not provide the freedom of action and equalized pressure control for the body as the supercharged plane does. Finally, the pressurized plane permits much quicker ascents and descents without causing discomfort so that it is preferable even at service ceilings where, normally, oxygen supply would suffice.

The final decision as to whether supercharging should be selected in lieu of oxygen, depends again on the time and facilities available to build war planes of this type in any appreciable quantities. Although several supercharged commercial models had been built before the war which can be modified readily for military purposes, such planes are the exception rather than the rule; oxygen equipment is still the most common solution for the time being. As in cabin-type planes, the oxygen supply system should be of the central and low-pressure type, with individual units for use in emergencies.

3.2 NONMILITARY. Compartment type planes for nonmilitary purposes are almost exclusively commercial transports, that is, cargo or passenger planes. The latter should, under all circumstances, be provided with central air supply coupled with the heating installation. Auxiliary ventilation should be effected by means of an individual fresh-air supply system as previously described. Foul-air spills are necessary for good circulation but must be well located and controlled. One or two common spills are preferable to banks of spills although the ducting is somewhat more involved.

Overhead systems are usually more efficient than floorboard or sidewall ducting. Their installation offers little difficulty on commercial planes, and their numerous advantages have been analyzed before. Diffusers should be selected as air inlets for the cabin itself while grilles or louvres are often more desirable in washrooms and galleys as well as in other areas where the head room is insufficient for the installation of diffusers. Grilles are also the most desirable form of outlets for used air.[1]

As recommended before, it is quite helpful to draw the expected flow of air into a perspective view of the cabin to make sure that the air distribution is in accordance with all requirements. This is particularly important in supplying air and heat to Pullman-type sections because inlets or outlets, which may be well located for passengers while they are seated during the day, may be utterly inadequate, if they have to serve passengers lying in a lower and upper berth.

Cargo planes do not require the intricate air supply system necessary for an airliner. However, the cargo to be carried may often depend on ventilation to prevent it from spoiling. For this reason, cargo spaces must have suitable means for ample circulation of both air and heat. Grilles and louvres, properly spaced, will usually serve this purpose very well. Adequate ventilation must always be provided for the flight deck and crew quarters, on cargo as well as passenger planes.

Supercharging is the ideal means for air supply on commercial planes of the compartment type, even at relatively low altitudes. It should be considered for all transports exceeding 8000 feet in regular flights.[2,3] On very large and cargo planes it is economical to supercharge only that portion of the plane which is normally occupied. In this case, it is advisable to provide decompression chambers to permit occasional access to un-supercharged parts of the plane without danger.

4.0 Ventilation on the Ground

Forced ventilation on the ground serves usually to permit either cooling or heating of the cabin during stop-overs. While the former is mainly a comfort feature, the latter may be so essential as to require its use on military aircraft.

Complete ground air conditioning is almost entirely reserved for commercial land planes, and is accomplished by means of elaborate ground equipment in which the ventilating air can be readily heated or cooled, and even de-humidified. Flying boats, however, cannot always make use of such facilities and should, if necessary, be provided with an integral ventilating blower for ground operation. Attempts to idle one of the engines and utilize the slip stream have not been very successful. Idling of one engine may, however, be used to drive the blower. This method is often employed, if the heating system depends on the operation of an engine (Fig. 36).

Forced ground ventilation by itself for military planes is very uncommon. Opening of the portholes, windshields and hatches must suffice, if lengthy stays are necessary. Where forced air supply on the ground is specified for military aircraft, it is invariably part of the heating system. In this case, the supplied air is merely a carrier and distributor of heat to such parts of the plane or equipment which require pre-heating before take off and, during emergency stop-overs in cold weather, the means to keep the crew and their quarters properly heated.

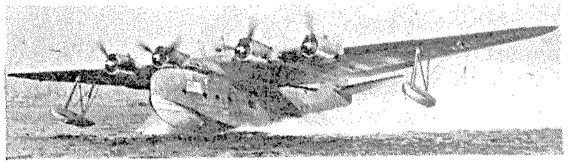


Fig. 36

References

[1] William C. Berchtold, "Heating and Ventilating Airplanes," *Heating, Piping and Air Conditioning*, August 1933.

[2] J. B. Cooper, "Altitude Conditioning of Aircraft Cabins," *SAE Journal*, June 1941.

[3] D. W. Tomlinson, "Airline Operations in the Sub-Stratosphere," *Aero Digest*, December 1940.

XII

REQUIREMENTS OF HEAT SUPPLY

1.0 Introduction

The requirements of air supply should be treated independently of heat supply although, in many applications, these two features are closely interconnected. The need for individual treatment becomes even more obvious in analyzing the complex requirements of heat supply on a modern airplane.

Inasmuch as cabin heating was looked upon as a luxury rather than an essential comfort it was, with a few exceptions, reserved for commercial airliners and, quite frequently, for the passengers alone. As far as military aircraft were concerned, it was not considered important until the war in Europe broke out. When British pilots, who were forced to fly at temperatures much below those ever encountered in flight before, suffered extremely from the cold, heat supply suddenly became a problem of the utmost prominence. Heavy flight gear, apart from handicapping fliers and impeding use of hands and feet, proved to be insufficient to prevent serious and, occasionally, fatal injuries even under average conditions, so that installation of suitable heating plants remained the only solution.

Once the designers were resigned to the need for heat on military airplanes, they quickly realized that it could be used profitably for an ever-increasing number of other applications. Heat supply was found not only to improve the operation of many accessories but even to prevent their failure at extremely low temperatures. Anti-icing and anti-frosting by means of heat proved to be the most efficient methods of overcoming the effects of icing and frosting. Ground heating permitted more rapid takeoffs and the immediate use of combat equipment. Thus, the tasks of heating were multiplied many times, and this within such a brief period that the development of adequate heating equipment could hardly keep pace with the increase in heating requirements.

Strictly speaking, the comfortization engineer is concerned merely with heat supply for flight crews and passengers. However, the problem of aircraft heating is such that it makes but little difference whether the heated object is a human being or a gun breech; the comfortization engineer is expected to plan and design the entire heating installation, without regard for its end use.

Consequently, the requirements of heat supply on an airplane comprise one or more of the following: (1) Heating of Flight Crews; (2) Heating of Passengers; (3) Heating of Accessories; (4) Heating of Miscellaneous Equipment; (5) Anti-Icing; (6) Anti-Frosting; (7) Ground Heating.

Before discussing the methods of calculating and meeting these requirements, it is advisable to study their scope briefly.

2.0 Heating of Flight Crews

In an excellent article on the problems of high altitude flight,[1] the *Fortune* Magazine quotes Major H. G. Armstrong, a leading aero-medical authority, as stating that ". . . studies of loss of pilot efficiency at lowered temperatures show that around freezing, when winter suits and heavy flying gloves must first be worn, efficiency drops 20%, while at −40° Fahrenheit, pilot efficiency may go down to 13% of normal. At this painfully low temperature the pilot is subject to deep mental depression and shows indifference to his mission and even to life itself."

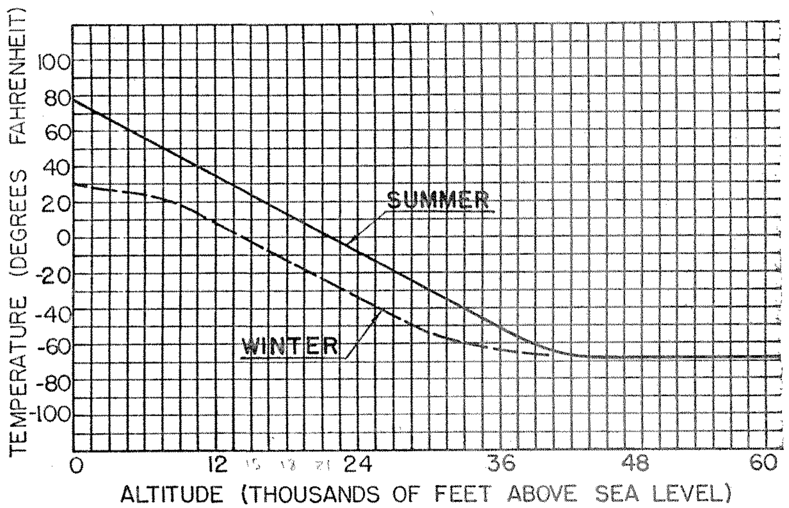


Fig. 37

The full significance of this statement is emphasized by the curve shown in Fig. 37 and, for military flight crews, even more dramatically in Fig. 38. As can be seen, temperatures drop almost proportionally with increase in altitude up to about 40,000 feet. At this height summer and winter temperatures not only become alike but remain constant at −67°, notwithstanding further increase in altitude. (All references to temperatures are in degrees Fahrenheit.)

These temperatures are merely averages. In reality, much lower temperatures have been measured at lower altitudes, and British fliers have reported temperatures much below −100°. Obviously, a considerable amount of heat is necessary to permit existence of human beings under these conditions, no matter how well they may be protected by clothing or heatproofing of the cabin.

Of course, not all planes are built or expected to operate at such extremes and in figuring heating requirements it would be impractical to base all calculations on the lowest possible ambient temperature which might conceivably be encountered in a few extreme cases. The data recommended in the table below have been compiled from the available, empirical information and should serve as a general guide for "Design outside, ambient temperature" (D.O.A.T.).

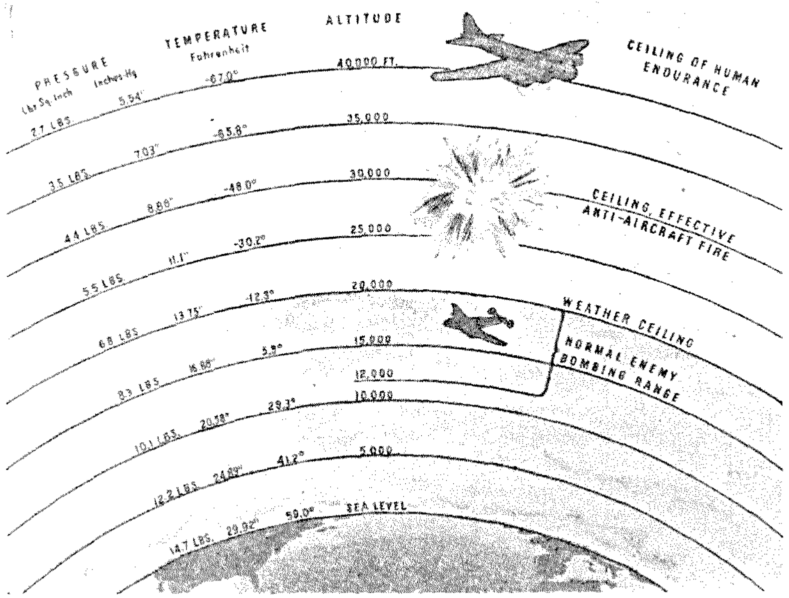


Fig. 38

The difficult task of achieving tolerable inside temperatures at these extremes is very much aggravated on military aircraft for a number of reasons: Planes of this type are often not at all and usually not as well heat-insulated as non-military craft. Numerous openings for the disposition of military equipment permit large infiltration of cold air. Heating plants must be more compact and lighter, and reasonably protected against damage during combat. Flying must be undertaken in any and all weather and entails operation of the plane in constantly changing climates.

RECOMMENDED DESIGN OUTSIDE, AMBIENT TEMPERATURES

Aircraft	Cabin	Ceiling (ft)	D.O.A.T. (°F)
Private	Non-pressurized	15,000	− 50
Private	Pressurized	25,000	− 70
Commercial	Non-pressurized	15,000	− 70
Commercial	Pressurized	35,000	−100
Military	Non-pressurized		−100
Military	Pressurized		−100

On the other hand, military flight crews do not require the close temperature control which is an important comfort feature on non-military planes, nor is it necessary to raise the temperatures beyond the level at which the average, healthy flier can perform his duties efficiently. In addition, military flight crews should wear a certain amount of protective clothing if only such portions of a large cabin are heated as are normally occupied. When passing through unheated sections of the plane or stationed near cold areas such as gun blisters a flier would be needlessly exposed, if the efficiency of the heating plant induced his superiors to discard even light, but warming flight gear. This is of particular importance because military flight crews might be compelled to bail out, at any time, with very low temperatures prevailing.

The design inside temperature (D.I.T.) for the cabins of military airplanes, with the exception of transports, need not be more than 60° and may vary plus or minus 5°. If spot heating is employed, normally unoccupied spaces within the fuselage should not be permitted to cool to less than about 50°, also with an allowable variation of plus or minus 5°.

Temperatures lower than the above have been suggested repeatedly and used. However, extreme chilling of unoccupied areas makes the heating of the occupied ones that much more difficult, and temperatures much below 60° for persons remaining at their stations for hours at a time are not compatible with the most elementary standards of comfort.

Military transports should be treated like commercial transports because they may be used for the moving of wounded, sick or otherwise weakened passengers.

Cockpit-type planes should be so heated as to keep the temperature within the cockpit at 60° plus or minus 5°, when the hood is tightly

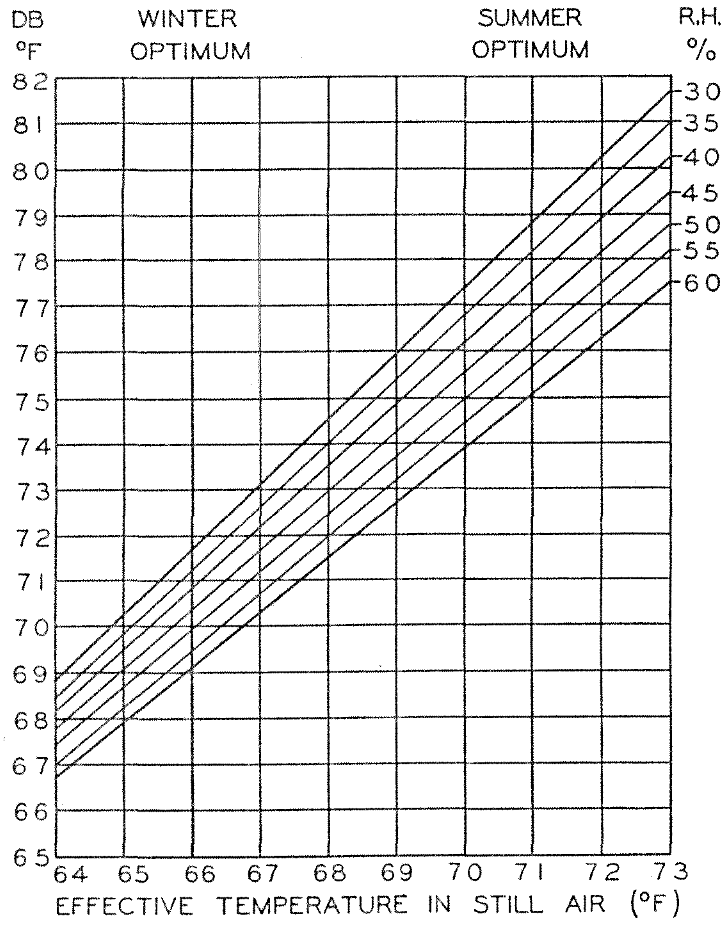


Fig. 39

closed. If the hood is open, the heat supply must suffice to keep feet and hands of pilot and gunner reasonably warm without the aid of heavy boots or gloves.

Heating requirements for flight decks and crew quarters of commercial airliners should be the same as for the passenger compartments.

3.0 Heating of Passengers

A.S.H.V.E. standards for adequate ventilation of enclosed spaces require that "the effective temperature shall range between 64° and 69° when heating or humidification is required, and between 69° and 73° when cooling or de-humidification is required. The relative humidity

shall not be less than 30% nor more than 60% in any case." These standards are illustrated in the curve shown in Fig. 39.

In order to provide the same comfort as exists in well air-conditioned spaces on the ground it would, therefore, be necessary to provide both humidity control and cooling in airplane cabins; but humidity control must be left for the airliners of the post-war period. Cooling of cabins in flight can, at present, be accomplished only by supplying cold air from the outside.

Under ordinary circumstances, the lack of cooling and humidity control will not be felt as severe discomfort. Still, it is necessary to consider these factors in the design of the heating system. As was shown, it is very desirable from a ventilating point of view to have as much as one complete air change per minute in the cabin. However, the introduction of that much cold air places a tremendous burden on the heating plant. For instance, the United Air Lines Mainliners, which employ this rate of circulation, require 160,000 btu/hr to obtain a temperature of 75° in the cabin, at an outside temperature of 0° and 8000 feet.[2] Furthermore, too much air flow will result in excessive dryness.

Too little air flow, apart from being undesirable for ventilation purposes, will result not only in stratification but also in high inlet temperatures. A further consideration is that of the low heat-storage capacity of the average cabin wall.

As A. E. Smith points out,[3] the outside temperatures may vary as much as 100° in two or three hours and even more than 10° per minute while, on the ground, they rarely change more than a few degrees per hour. According to Smith, the heat-storage capacity of the normal cabin structure (noninsulated) is only 0.22 btu/°F for every square foot. Consequently, changes of outside temperatures are almost immediately felt by the passengers. Since the outside wall is usually within 3° of the surrounding air, the trim surface temperature may be more than 15° below the cabin temperature and that of window areas even 30° to 40° below.

Smith then emphasizes that, normally, only a small percentage of the body heat is removed by convection while about 60% of it is lost by radiation to surrounding walls, floors, ceiling and furniture. Considering the low heat-storage capacity of the airplane structure, and the rapid and large changes in ambient temperature, very good circulation is required to balance the radiation and convection loads.

To decrease the burden on the heating plant it would seem advisable to resort to some degree of recirculation. This method, however, cannot be recommended, save for exceptional cases, as there are no effective means to remove smoke, body and other objectionable odors from the recirculated air.

Under these conditions, there remains only the installation of a heating plant large enough to provide the required amount of heat to the ventilating air so as to assure satisfactory circulation at all times. Proper distribution of heat supply and good heatproofing will greatly reduce the over-all heat losses and heating load.

Since passengers are normally at rest and clothed as they would be in a heated room on the ground, temperatures should be as close to 70° as possible. On sleepers, the temperature should average 68° during the night.

Large temperature variations are not desirable. On the other hand, the limited rate of circulation and the conditions discussed above would make it extremely difficult to establish very close limits for temperature variations throughout the cabin. Therefore, a variation of plus or minus 3° appears to be an acceptable compromise.

Requirements for military transports may be somewhat relaxed, and an average temperature of 67°, with a variation of plus or minus 3° is not unreasonable. Transports for carrying paratroops and other passengers accustomed to air travel can even go below this figure, and allow for average temperatures of 65° with variations of plus or minus 5°.

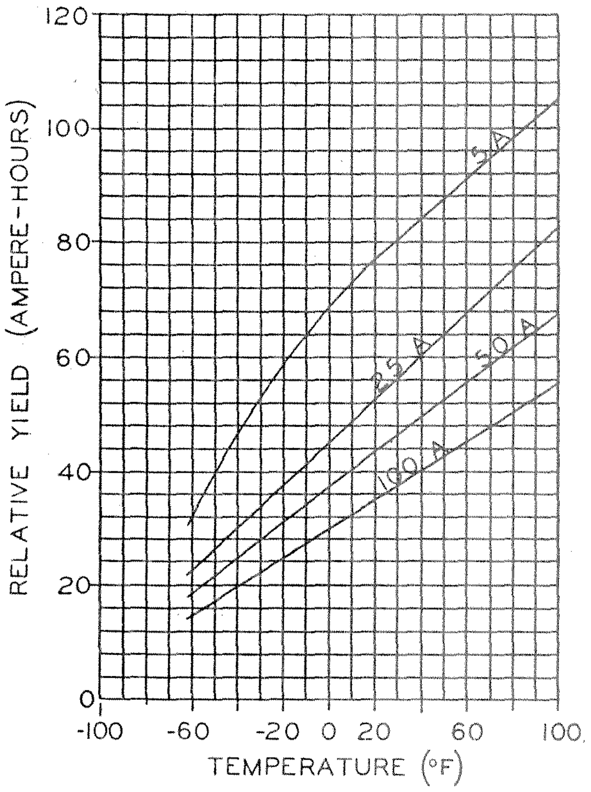
Military utility planes, such as ambulances, laboratory and planes used for evacuation and similar purposes should always be considered as having heating requirements similar to those of commercial transports.

4.0 HEATING OF ACCESSORIES

While adequate heating is needed for the physical comfort of flight crews and passengers, heating of accessories has become of even greater importance for the efficient operation of the airplane itself.

This applies to both the flight as well as "purpose" accessories, particularly those on military aircraft. Among the flight accessories, requiring heat supply, are, for instance, the gyro instruments and the storage batteries whose efficiency is greatly reduced at low temperatures as shown in Fig. 40.

Among military accessories which must be kept above certain temperatures in order to perform efficiently are gun breeches and gun-turret mechanisms as well as the bomb sights which require heating to prevent condensation on the lenses. This is equally true for photographic equipment. Proper heating of the latter is not simple because the temperatures must be very uniform throughout and well controlled.



SOLAR AIRCRAFT COMPANY HEATER DIVISION GBH

Fig. 40

If the frequently-used infra-red film is subjected to too much heat, "fogging" and dark spots may result. Even the ammunition magazines should be heated, because moisture tends to condense on them and freeze, preventing injection of the shells into the breech and, possibly, resulting in explosions within the barrel.

Rapid changes from and to great heights are mainly responsible for failure of unheated accessories. Therefore, every device and instrument must be tested in the cold chamber on the ground, and its operation must be observed at various and fast-changing temperatures. Only such a procedure yields the data on which the correct amount and method of heat supply can be based.

In many cases these data are readily available, often they are specified. For obvious reasons these figures are confidential. Generally, however, a temperature of about 40° will be found to be the minimum at which most equipment will still perform in accordance with specifications.

If cooling is required, circulation of air is almost invariably the most practical method.

5.0 Heating of Miscellaneous Equipment

In addition to the standard accessories there are other applications for the supply of heat, for instance, on galleys. Facilities for preparing warm meals or for keeping food warm are of considerable importance. The heat supply required for these purposes may vary from small amounts for boiling coffee to enough to permit the preparation of several complete, warm meals at a time.

Another military application is occasional need to heat rather large quantities of water. Warm water is also required on commercial planes, not only for the preparation of food but also for lavatory purposes.

Considerable ingenuity may have to be expended to design a suitable heating installation and distribution system for cargo planes. Ordinarily, cargo spaces should be heated evenly to a temperature of not less than 50°, with a variation of plus or minus 5°. Similar temperatures should be provided for separate cargo spaces of both commercial and military transports.

There may be other special devices or apparatus such as surgical or laboratory apparatus which are not exactly component parts of the airplane but which require heating for proper operation. To assure optimum performance, it should be a rule always to examine them not only for meeting the specifications for the particular functions which they have to fulfill but also their operation at low temperatures. It would be unwise to reject equipment of this type merely because it fails at low temperatures, although it may be very suitable in any other respect. The scope of heat supply has grown to such an extent that proper means for heating can be found for almost any purpose and application.

6.0 Anti-Icing

The accumulation of ice on the wings of an airplane, particularly, along the leading edges, has long been recognized as one of the most serious hazards in flying. C. S. Stebbins[4] summarizes the reasons for icing by stating that this phenomenon is caused by the presence in the atmosphere of tiny water droplets which range in size from 0.01 mm to more than 2 mm in diameter, at temperatures far below the freezing point of water, which turn instantly to ice upon contact with the wing of a plane.

Ice may also form from saturated or super-saturated air masses. Ice forming conditions have been observed in a temperature range from plus 54° to 44° below. Icing may occasionally occur at rather high temperatures. A. N. Troshkin of the C.A.B. Safety Bureau[5] warns to be "ice conscious" at 70° and below.

In some weather conditions the normal operation of an airplane may be affected in less than 5 minutes. In addition to forming on the leading edges of wings and control surfaces, ice accumulates also on the propeller, often with disastrous results, as flinging ice may deform the blade profile and cause unbalance.

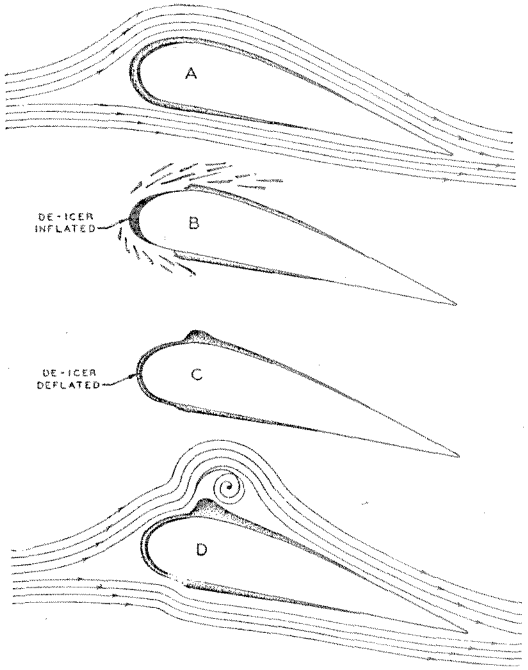


Fig. 41

According to a widely publicized report, the British lost their highest percentage of bombers during a raid over Germany because they encountered unexpected icing conditions although the entire flight had been carefully planned.

Research in the removal of prevention of ice accretion is over twenty years old and was particularly encouraged by the airlines which recognized icing as the greatest obstacle in their endeavor to make commercial flying safe. Dr. W. C. Greer, former research director of the B. S. Goodrich Company, tried to apply a paint with rubber base to the wings to prevent ice from adhering. Finally, he developed the first model of what is known today as the "rubber boot de-icer." This principle is still the most popular method of ice removal, and a great number of improvements have been made in the meantime.

In spite of these improvements, the method of forcibly removing existing ice formations—commonly termed "de-icing"—is not always satisfactory. It requires a rather complex mechanism. If any one of its many parts fail, the entire system may be inoperative. Big pieces of the cracked-off ice may be thrown against other parts and damage them. Under certain circumstances, de-icing may be even more dangerous than icing itself by deforming the airfoil.

Dr. Alexander Klemin, a foremost authority on aerodynamics, has used an ingenious method to make visible the flow of air past flat plates and airfoils of various shapes and at different angles.[6] His patterns show convincingly the importance of preserving the shape of the leading edge as well as that of the areas adjacent to it. Accordingly, if a condition arises as described above, the following may take place:

Referring to the sketches in Fig. 41, sketch *A* represents the cross-section of an airfoil provided with rubber boot de-icers upon which ice has accumulated. Sketch *B* shows the same wing section after the de-icer has gone into action. Note that only the layers on top of the de-icer have been removed while the ice sheet on the upper surface of the wing, due to exceptional adhesion, has not been blown off. Sketch *C* illustrates what will happen to this sheet after a few more minutes. The wind has rounded off its leading edge and additional ice has formed on it, resulting in a contour approximately as shown.

Therefore, the air will flow over the thus distorted airfoil as indicated in sketch *D*, and the wing stalls. Inasmuch as most of the lift is contributed by the upper surface of the wing, its deformation and loss of lifting power will cause the plane to drop.

Dr. Greer considered heating of the leading edges of the wing to thus prevent the formation of ice altogether. Such a method is called "anti-icing." Little was accomplished in this direction because the heat quantities required were so large that none of the then existing primitive heating plants could furnish them.

However, the Germans have used anti-icing for quite some time. It is reported[7] that such an installation was found in a captured Dornier DO 217E heavy bomber. Hot air was piped through the wings, and provisions were made for hot air sprays against the windshield and each of the windows in the nose. No anti-icing was provided for the control surfaces. The propeller was de-iced the same as on American aircraft today: by means of slinger rings and anti-icing fluid.

Mainly due to the untiring efforts of the N.A.C.A., anti-icing is finding growing support in this country and will, undoubtedly, increase during the next few years.

The main disadvantages of de-icing are eliminated in anti-icing and impaired operation or failure of the aircraft, even under the severest icing conditions is prevented. If the heating plant should, for some reason, not suffice for complete prevention of icing, conditions improve as the ice layer increases since it acts as a heat insulator and permits the wing structure to increase its temperature. Thus, even an insufficient amount of heat will, finally, melt the ice.

For military aircraft which has to fly in all types of weather and cannot readily avoid icing conditions as can the non-military craft, anti-icing becomes one of the most important and valuable aids in flying. The main obstacle to making anti-icing installations universal are the vast heat quantities required for this purpose. However, there are a number of heating systems available or being developed which will easily supply the required heat. These systems will be discussed in a subsequent chapter.

Anti-icing of the propeller is effected by means of slinger rings near the hub which exude an anti-icing fluid. The centrifugal force then spreads the fluid along the blade. Although this method is quite successful, there is little doubt that, ultimately, heating will be employed for this purpose, too. The use of an anti-icing fluid entails several problems and is not quite as efficient and simple as heating of the blades.

7.0 Anti-Frosting

Often considered as part of the anti-icing scheme of the heating system, the removal of frost and fog from transparent surfaces is actually a problem in itself. The formation of ice or condensate on the windshield, portholes, or the lenses of gun and bomb sights, photographic and similar equipment is dreaded by military fliers not less than icing. Although it is by no means desirable, a commercial plane can always change its course and altitude, make an emergency landing, or postpone a flight altogether to avoid unsafe weather.

The military plane must operate under any and all conditions and, it is necessary to provide effective de-fogging and de-frosting equipment. The already quoted C. S. Stebbins, for example, mentions a report by an R. A. F. pilot who stated that, at an outside temperature of −75°, crystalline frost formed on the windows which was 3/4″ thick. The windshield had to be kept open entirely in order to permit vision. The danger of such a situation, particularly during combat and missions over enemy territory, is quite obvious.

In experimenting with numerous systems and methods it has been found that flush windshields assist in decreasing the formation of ice. Deflectors on the outside of the glass have given fair results, but they do not seem to be satisfactory at high airspeeds. Other means which have been tried were freezing-point depressants, windshield wipers, inflatable and transparent elements, jets emitting air at high velocity and many more.[11]

While none of these methods has been of much use, it appeared that heating can effectively prevent not only frosting but also fogging of windshields and other transparent surfaces. It has been shown that circulation of air at a temperature of about 165° will keep these surfaces clear on both sides under most circumstances. Since this method is one of prevention rather than removal, it should be termed "anti-frosting" as a parallel, in every respect, to anti-icing.

Electric heat applied directly or by radiation has not proven very feasible, which is explained by the following consideration: The dew point corresponding to air of 70° temperature and 30% relative humidity is 36° which is lower than the temperature of the average window surface, if good circulation is provided. However, if the temperature of the dew point rises or the air circulation should become insufficient, condensation will result on all cold areas and, before all, on the transparent surfaces.

For this reason it is necessary not only to heat these surfaces but also to provide a sufficient amount of circulation. Since this requires the flow of heated air, anti-frosting can very well be made part of the cabin heating system.

There are two ways of supplying both heat and circulation to a windshield or porthole. The first method consists of a flexible duct which is branched off from the main hot-air duct and mounted perpendicularly to the surface to be heated. Thus, a blast of hot air is directed toward it which, if adequate, will prevent the formation of condensation on the inside and frost on the outside.

Devices of this type are quite common since they are simple to install and require but little added weight. On the other hand, they must furnish a considerable amount of hot air in order to be effective. As the air stream is deflected back into the cabin, the heat contained in it is usually not lost. However, if such a scheme is used for the anti-frosting of a windshield, the reflected hot air blast may cause very much discomfort to the pilot and co-pilot.

For this reason, the so-called *double-pane* construction, as originally proposed by the NACA, holds very great promise. Such a construction has been developed by United Air Lines and is employed successfully on the windshields of their Mainliners. These windshields consist of

an outer pane of solid plate glass, ¼" thick, and an inner pane of ⅜" laminated safety glass. The panes are separated by a ¼" air space through which about 60 cfm of air at a temperature of 175° are circulated.[8,11]

After many tests and changes, the present installation has proven to be very satisfactory. In addition to its usefulness in anti-frosting, it is an excellent heat and sound insulator as well as good protection against bird-strikes. Its main disadvantage is somewhat inferior optical quality, particularly on account of multiple reflection of lights in the flight-deck. As reported by R. L. McBrien of the United Air Lines staff,[11] pilots also complained about being bothered by the strain lines in the tempered glass which became very marked with the use of polaroid goggles.

There is no doubt that further developments will eliminate these disadvantages. However, such a construction for the windows in the cabin is still impractical on account of the large weight which it entails. Experiments with plastics have shown that the presently available materials are not yet quite suitable for this purpose, but diligent research is continued in this direction.

8.0 GROUND HEATING

The tasks of ground heating aircraft can be divided into two distinct functions, namely heating of personnel and preheating of engines and accessories.

The actual need for ground heating should be very carefully investigated. If it is absolutely essential, only such combinations must be selected as avoid separate equipment for flight and ground heating. In planes where the latter is needed only in exceptional cases, it will often be found that idling of one engine for operation of an engine-operated heating system is a satisfactory solution.

Whether and when an airplane heating system should be operative on the ground depends on the conditions in each case. Land planes for commercial transport usually do not require such a system; they can be served by the portable ground heating equipment which is available at practically all airports. Nor is preheating of equipment required for these planes since they are kept in well heated hangars when grounded for any length of time. Similar considerations apply to other non-military planes which are rarely exposed to severe cold on the ground long enough to make a ground-heating installation feasible.

Conditions for military planes are entirely different. These planes may have to stand on emergency landing fields over night or even for several days without hangar facilities or other protection from extreme cold. On the other hand, quick take-offs after lengthy exposure to low temperatures may be vital. This can be best accomplished by the ground heating of engines and other accessories.

The time required to warm up an engine may be of the greatest disadvantage in the execution of military duties, and after a brief warm-up time an engine is liable to fail during or shortly after take-off. Thus, proper means for preheating the engine not only permit speedier take-offs but also decrease the danger of early engine failure.

The Germans have accomplished take-offs with stone-cold engines by using a mixture of ether and gasoline for priming which is carried in a supplementary tank. A secondary tank is filled with a fuel mixed with a small percentage of oil to be used during take-off and climbing. No switch is made to the regular gasoline until normal conditions for flight and operating temperatures for oil and coolant are reached. Such an installation has been found, for example, in the Mercedes-Benz DB-601A aircraft engine as reported by Raymond W. Young.[9] Whether such a method is preferable to preheating and conducive to good engine performance and life is doubtful. However, quick take-offs are usually of more importance for the military plane than a few more hours of engine life.

American engines are often preheated by portable ground heaters or by placing a tent over the nacelles and heating the insides of these tents with a small stove, fueled either by gasoline, oil or a petroleum gas. Electrically heated blankets are sometimes used for the same purpose. None of these methods are very satisfactory since they entail service and equipment available only at regular bases. For this reason, ground heating equipment should always be investigated for its adaptability to engine preheating, thus greatly adding to its usefulness.

The ground preheating of certain instruments and equipment is often even more important than preheating of engines. For instance, a heavy-calibre cannon in a plane which has been exposed to low temperatures through standing on an unprotected field for many hours will not function properly for some time after the starting of the heat supply, since its large mass of cold iron requires much heating before the breech mechanism is warmed up sufficiently. However, if the cannon has been kept at a reasonable temperature while on the ground, it will operate immediately after take-off, which often may spell the difference between life and death. Among the equipment requiring ground heating are also the gyro instruments and most of the engine accessory section.

In general, ground preheating is urged for such accessories which, unless suitably heated, may not only jeopardize the success of military maneuvers but also suffer damage beyond repair, even keep the plane grounded. Furthermore, anti-icing and anti-frosting should continue on the ground, whenever necessary and feasible, lest valuable time be lost before take-offs. The accumulation of ice and snow on wings may be so severe that take-offs are delayed, if not made impossible for considerable periods of time. By the same token, anti-frosting will permit use of optical instruments and vision through windshields and portholes immediately after the take-off.

Frequently, stopovers of some duration are necessary, during which the flight crew or passengers may have to remain inside the plane and, possibly, even use it as living quarters. In such cases adequate heat supply for cabin heating on the ground is highly desirable and should be provided, if at all possible.

Specifications for ground heating vary greatly and often are subject to personal opinion. Although ground heating and preheating are very helpful and often mandatory, the numerous limitations placed upon the military airplane do not always permit installations for this purpose. Since no external sources for power or air supply can be depended upon, integral blowers and, in some cases, power-generating equipment must be employed.

Therefore, ground-heating equipment is not usually favored for fighters, interceptors and similar cockpit planes although they require it as much and, frequently, even more than the larger planes. This becomes evident when it is realized that fighters may have to take off and be fully operative at a moment's notice.

Many cockpit-type planes employ heating systems dependent on engine operation. In this case it is necessary to keep the engine running on the ground so that the heater may function. While ground operation of such heaters could be limited to the engine warm-up period, there still is need for a blower to supply the necessary air. For these reasons ground heating should be specified for cockpit-type planes only where its lack would decidedly interfere with military purposes.

In the larger planes of the cabin and compartment types installation of ground-heating systems is easier. In spite of that, it must be carefully ascertained whether the advantages of such equipment outweigh the disadvantages.

Heating requirements on the ground are usually very much smaller than those in the air. Because the plane is standing still and the maximum air speed is only that of prevailing ground winds, heat losses are decreased. Unless the crew or other occupants have to stay within the plane, cabin temperatures may be far below those required during regular occupancy and raised only shortly before take-off. The minimum design ambient, outside temperature can also be higher on the ground but should not be above −60°.

Accessories should be kept at temperatures somewhat above freezing, preferably around 40°. Engines which do not use a dilution system should not be allowed to cool below 32°. If a dilution system is used, the engine auxiliaries such as starters, carburetors, oil pumps and batteries should be kept between zero and 40°. Wings and control surfaces should be heated to about 40°, if necessary, in order to prevent the accumulation of ice and snow. Heat supply to transparent surfaces must remain high enough to avoid condensation and frosting.

In specifying ground heating it is important to compare the requirements for heating on the ground with those made for flight so as to facilitate the use of the same equipment for both purposes. Unfortunately, it is not always realized that considerable latitude must be given to the designer so as to avoid duplicate equipment.

Similarly, specifications should not call for features which would unnecessarily complicate the installation. Heaters which can be removed on the ground so that they may be used for heating jobs outside of the plane should not be specified. Multi-purpose devices of this type are inefficient, heavy and complicated.

Sometimes, ground heating is specified for 24 hours a day without the use of an outside power source. At the same time, it is stated that no drain on the batteries is permitted. In such a case, weight allowances must be made for carrying an independent source of power supply. Ordinarily, a small current drain should be permitted at least to operate the necessary electrical controls, as it would be unwise to add power-generating equipment for the supply of a few watts.

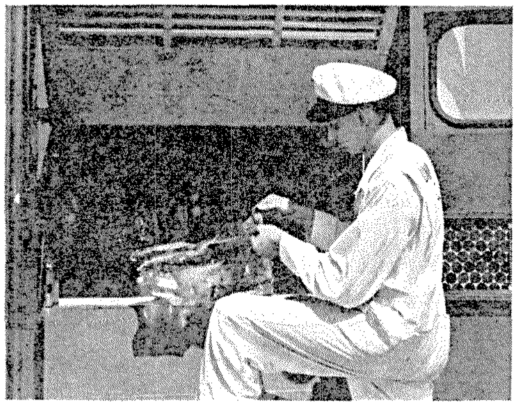


Fig. 42

Specifications should, preferably, be limited to the mere statement that ground heating is desired and, at the most, to an enumeration of the devices which should be heated as well as their optimum operating temperatures. It should be left to the comfortization engineer to design and select his equipment in such a manner as to meet all requirements without in any way burdening the plane or its accessories beyond the absolute minimum.

No provisions for cooling are necessary on military airplanes. Circulation of fresh air by opening windows and hatches must be sufficient. Cooling as a feature of complete air conditioning is effected for commercial airliners by equipment described, in detail, by Fred Erbach.[10] Instead of chemicals, regular ice is employed in United Airlines' "comfortizer" for air conditioning their Mainliners on the ground (Fig. 42). 800 pounds of ice in the truck last 12 hours and deliver six tons of cooling, according to United's engineers.

Such a method is possible only as part of the extensive customer service rendered by the commercial airlines, and is neither feasible nor necessary for military purposes.

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XIII

CALCULATION OF HEAT REQUIREMENTS

1.0 INTRODUCTION

The calculations of heat requirements for an airplane are only approximations since they are based largely on assumptions and empirical data. This is not surprising as the transfer and loss of heat takes place at temperatures, densities, humidities, and air speeds never before experienced.

These conditions apply primarily to the modern, military airplane and are aggravated by the fact that military considerations result in fuselage constructions which make the control of infiltration and heat preservation quite difficult.

In spite of that, sufficient data have been collected during the past few years to permit comparison with calculated values so that the simplified methods for calculation as shown in the following should be conclusive enough for selection of adequate heater capacities. (For the sake of simplicity, heat quantities will be frequently expressed in terms of *stu*—standard thermal unit—which equals one thousand btu/hr.)

2.0 HEAT REQUIREMENTS FOR COCKPITS

It is neither feasible nor possible to heat the air space within a cockpit uniformly, unless it is very well sealed and insulated. In this case it becomes a small cabin and must be treated as such.

The most practical method of heating a cockpit is by providing a spot heater which emits a blast of warm air towards the lower extremities of the pilot, with an additional and separate installation for a second cockpit. If the hood is open, there is a strong draft blowing from the lower forward to the upper aft portion of the cockpit, and the heater must be so located that the emitted air stream is aided rather than opposed by the motion of the draft. This will assist in bringing warm air to the hands, face and neck of the flier.

The warm air inlet which, in spot heaters, is often located in the heater housing, should not be too close to the body of the occupant as the necessarily high inlet temperatures would cause considerable discomfort. If the inlet is too far away, little or no benefit is derived from the heater. Notwithstanding structural limitations and obstructions such as the control column, cables and the like, the inlet should be not less than 3 nor more than 5 feet from the legs of the occupant. The inlet temperatures are preferably between 150° and 170°. These temperatures may seem high, but cooling and dissipation of the air stream is so rapid that lower temperatures are not desirable.

Experience has shown that from 10 to 20 stu of heat are required per person or cockpit. The choice of the lower or higher values depends on the speed and ceiling of the plane, its operating conditions and the design outside, ambient temperature (D.O.A.T.). If the desired heat quantity and temperature differential have been selected, the necessary air flow can be calculated from the following formula:

$$H = 60cqd(t_2 - t_1) \qquad (1)$$

where H = Heat required, in btu/hr;
c = Average specific heat of air, in btu/lb/°F;
q = Quantity of air supplied, in cfm;
d = Average density of air, in lb/cu ft;
t_2 = Cockpit inlet temperature, in °F;
t_1 = D.O.A.T., in °F.

It shall be assumed that a heater capacity of 10 stu and a D.O.A.T. of −60° have been selected. The average specific heat of air is 0.24 although it changes somewhat with temperature. The average air density at sea level is 0.075 lb/cu ft. Then, for an inlet temperature of 150°:

$$10{,}000 = 60 \times 0.24 \times q \times 0.075 \times (150 + 60)$$

and:

$$q = 44.1 \text{ cfm}$$

Accordingly, this amount of air must be provided at sea level to raise a minimum outside temperature of −60°F to 150° after addition of 10 stu. It so happens that this is only a little over the amount specified for the average ventilating needs per person. While this is a very acceptable value, the temperature at sea level will be mostly higher than −60°. Assuming that it is 0° and all other factors are kept constant, the inlet temperature would be raised to 210° which, of course, is far too high. In order to avoid this, it is necessary either to increase the air flow, or to provide the heater with a modulating control which permits the decrease of its output. Offhand, the latter seems to be the simpler solution.

As the plane ascends and the air density decreases, the temperature of the inlet air would again become too high, unless the air flow is increased to equal the mass flow at sea level, or the output of the heater is decreased. Obviously, the latter is undesirable since normally more heat is needed at altitude than on the ground. For these reasons, provisions must be made both to increase the air volume with increasing altitude—preferably by means of an automatic damper—and to decrease the output of the heater for higher outside temperatures, which should be done manually. The curve shown in Fig. 43 gives the factor by which the air volume at sea level must be multiplied to retain the same temperature differential at all altitudes. This factor is the ratio of d_s, the density at sea level, to d_a, the density at altitude.

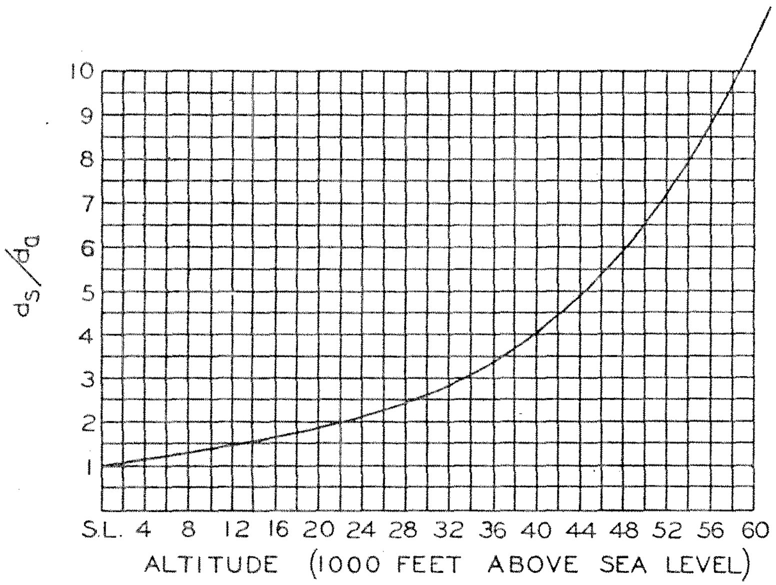

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Fig. 43

The higher the rated capacity of the heater, the greater air quantities must be furnished. Since air for this purpose is usually obtained through a scoop, such increases should be avoided because they result in greater outside drag and inside drafts. Control of air flow will relieve these conditions somewhat but not sufficiently to permit more favorable figures for heat output and inlet temperatures. As a rule, the designer should increase inlet temperatures to the allowable maximum, rather than decrease the heater output below what he feels is required.

Another solution of the problem of cockpit heating is the provision of electrically heated flying suits which will be discussed later.

3.0 HEAT REQUIREMENTS FOR CABINS

In calculating the heat requirements for aircraft cabins it is necessary to make two assumptions which seldom, if ever, hold true. The first assumption is that the cabin is very well sealed and insulated, and the other is that the worst possible conditions exist outside and there are no persons or devices inside of the cabin which contribute heat.

The heat supply to the cabin must balance the heat losses minus whatever heat may be furnished by other sources. Heat is generated and dissipated by such devices as lamps, motors and similar equipment. However, the quantities gained in this manner are so small that they can be disregarded. Considerably more heat is contributed by the metabolic rate of the occupants. As compiled by the A.S.H.V.E. Research Laboratory, the total heat dissipated by individual persons will range from 0.3 to about 0.6 stu, according to their activity. For persons on the ground and doing heavy manual labor the hourly heat generation may be as high as 5 stu. Taking an average of 0.5 stu for the occupants of an airplane, it can be readily seen that an occupancy of 40 crew members and passengers will generate as much as 20 stu which represents a considerable amount of heat.

As mentioned before, it is necessary to base all calculations on the worst possible conditions which, in this case, would mean that only a very small number of people is in the cabin and active in such a manner as to dissipate a negligible amount of heat. For this reason it can be assumed that no heat is contributed by any other sources and that the heating plant must furnish all requirements to balance the heat losses.

Accordingly, the amount of heat which must be supplied by the heating system is determined by the ventilation requirements, the heat loss by transmission through the plane outline and the heat necessary to offset the infiltration through cracks around windows, doors, and other openings. Since it was assumed that infiltration of air is minimized by well-sealed doors and windows, and the creation of a positive pressure in the cabin, it shall be neglected too, for the time being. Thus, there are only two factors which have to be considered in the calculation of heat requirements, namely ventilation and transmission.

3.1. VENTILATION HEAT LOSSES. In order to determine the heat requirements for ventilation purposes it is necessary first, to establish the ventilation rate and, second, to calculate the cubical content of the cabin. Assuming that, in a specific example, it has been decided to change the air within the cabin 30 times per hour—that is one complete air change every two minutes—and that the cubical content of the cabin is 2500 ft^3, then 1250 cfm of fresh and cold air must be heated.

H_v, the heat amount for ventilation, is then found by means of formula (1). The average specific heat of air can again be accepted as 0.24 btu/lb/°F. The desirable cabin temperature shall be specified as 70°. The D.O.A.T. at the service ceiling is to be $-100°$. If the service ceiling of the plane is 20,000 feet, the minimum density of the air is 0.04 lb/ft^3 (see Fig. 20). Thus,

$$H_v = 122{,}400 \text{ btu/hr or } 122.4 \text{ stu.}$$

At this ceiling the partial pressure of the oxygen in the air is, of course, insufficient for human needs and oxygen equipment must be used. Therefore, the air now serves merely as a carrier aand distributor for the heat, unless the cabin is supercharged. The conditions in this case will be discussed shortly.

As the plane descends to sea level, the density of the air increases. On the other hand, the temperature differential decreases. Substituting the value 0.04 for d_a with 0.075, and $-100°$ with $-60°$,

$$122{,}400 = 60 \times 0.24 \times 1250 \times 0.075 \times (t_2 + 60);$$

and: $t_2 = 30.8°$

Obviously, this value is too low for a comfortable cabin temperature and, consequently, the capacity of the heater insufficient. This proves that, in order to obtain the maximum amount of heat which the heater may have to supply, the heater requirements must be calculated for sea-level conditions.

Then: $H_v = 60 \times 0.24 \times 1250 \times 0.075 \times (70 + 60)$
and: $H_v = 175.5$ stu

This value is considerably higher than the previous one. In order to find the corresponding cabin temperature at the service ceiling, the following formula can be used:

$$t_{2a} = t_{1a} + (t_{2s} - t_{1s})d_s/d_a \qquad (2)$$

in which the suffixes *s* and *a* denote sea level and altitude at the service ceiling, respectively. Inserting the D.O.A.T. and d_a at a service ceiling of 20,000 feet, and obtaining a value of 1.875 for d_s/d_a from Fig. 43,

$$t_{2a} = 144°$$

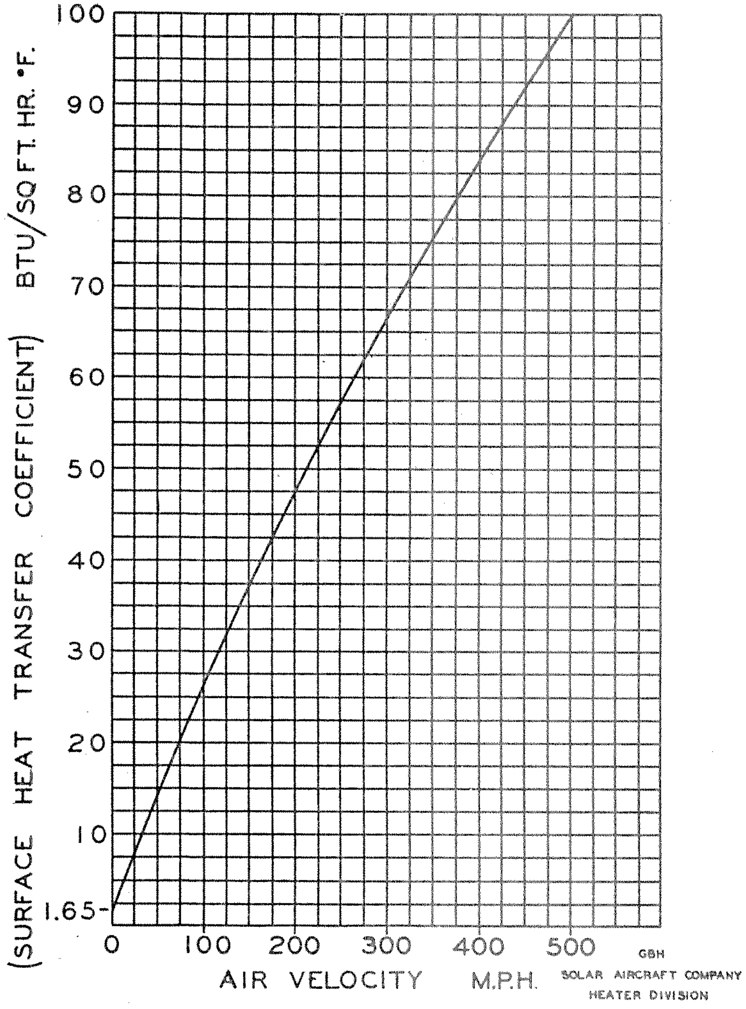

Fig. 44

Since this temperature is too high, an increased amount of cold air must be introduced which can be found by means of formula (1) as follows:

$$175{,}500 = 60 \times 0.24 \times q_a \times 0.04 \times (70 + 100)$$

and: $q_a = 1780$ cfm

Therefore, an additional 540 cfm of cold air must be supplied at 20,000 feet in order to keep the cabin temperature at 70°, with a minimum outside temperature of $-100°$. Since the temperature control on most planes equipped with central heating systems is based on the proportioning of hot and cold air, the additional air needs can be easily furnished.

Incidentally, the above calculations illustrate how important it is to check the air supply not only for the requirements of ventilation but also for those of heating.

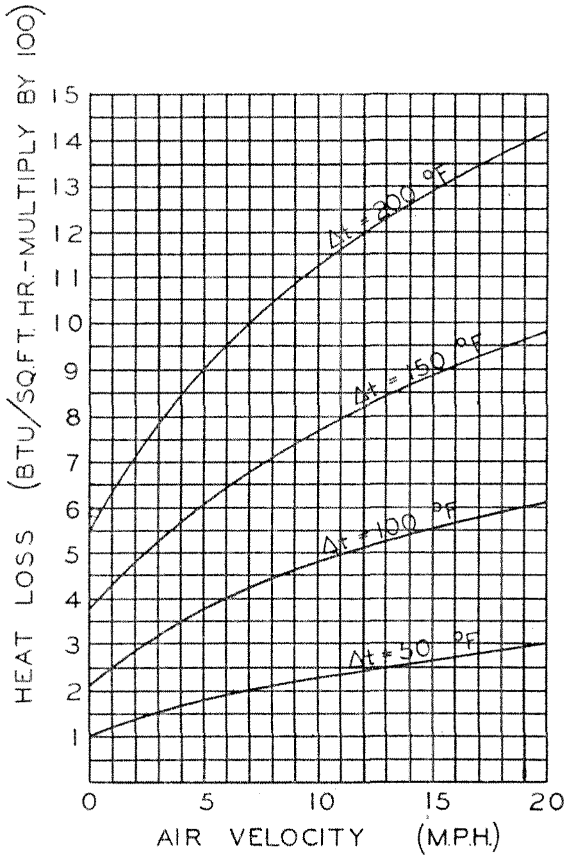

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Fig. 45

3.2 HEAT LOSS THROUGH THE PLANE OUTLINE. The heat loss due to transmission is caused by the transfer of heat from the warm cabin air to the walls, ceiling and floors of the plane, and hence to the outside. It is calculated by means of the following formula:

$$H_t = A \times (t_2 - t_1) \times U \qquad (3)$$

in which: A = Area of the transmitting surface, in sq ft;

t_2 = Cabin inside temperature, in °F;

t_1 = D.O.A.T., in °F;

U = Overall heat transfer coefficient, in btu/hr/ft²/°F

The overall heat transfer coefficient is established by the following equation:

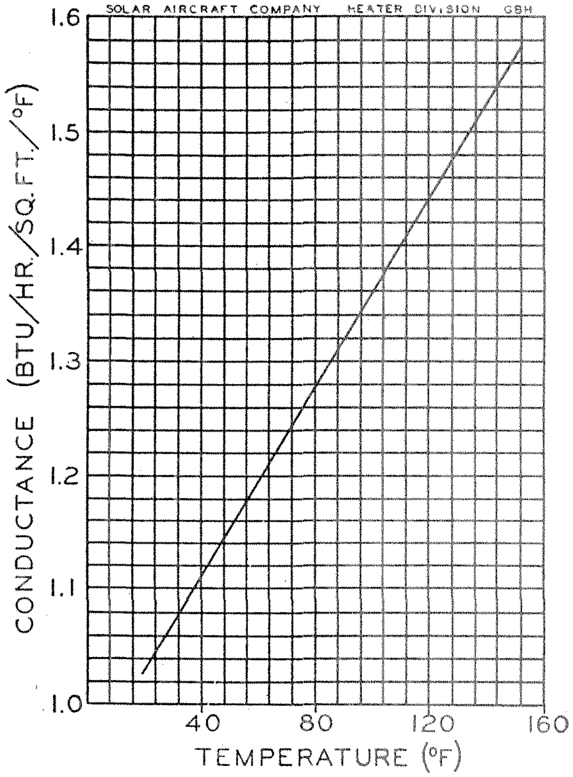

Fig. 46

$$1/U = 1/f_i + 1/f_o + 1/C + x_1/k_1 + x_2/k_2 + \cdots \qquad (4)$$

f_i and f_o represent the inside and outside surface heat transfer coefficients, respectively. They are the coefficients of thin layers of air immediately adjacent to the surface, and may influence the heat transfer considerably, particularly at high air velocities. C represents the conductance of the air space. x_1, x_2 etc. are the thicknesses of the insulating materials in inches. k_1, k_2 etc. are the respective heat transfer coefficients for these materials in btu/hr/ft²/°F/in.

The accurate calculation of the surface heat transfer coefficients is quite involved,[1] but in practically all cases it is sufficient to use approximations. Since the movement of the air inside the cabin is comparatively slow, 1.65 can be selected as an average inside coefficient,[2] while

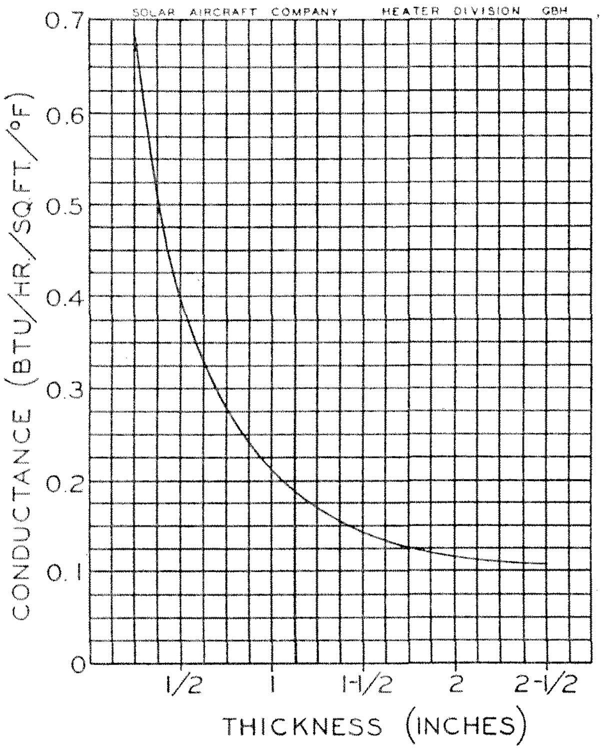

Fig. 47

the curve shown in Fig. 44 furnishes very useable values for the outside surface coefficient at various air speeds and moderate temperature differentials. More details will be found in Chapter XVI.

The set of curves shown in Fig. 45 offers an interesting comparison. These curves represent the heat transfer from hot surfaces to air, in btu/ft²/hr, at various air velocities and temperature differentials. They have been plotted on the basis of conservative values compiled by Langmuir and shown in Marks' *Handbook.*

The conductance of the air space can, for the sake of simplification, be assumed to remain constant at 1.10 btu/hr/ft²/°F of temperature difference. According to tests by Wilkes and Peterson, as quoted in the *HVAC Guide*, the conductance changes little for air spaces ¾″ or more in width. The curve in Fig. 46, which represents the thermal conductance of a 1″ air space at various temperatures, proves that changes in temperature have some effect on the conductivity.[4] However, it will be found that, in most aircraft heat calculations, these changes can be disregarded. The conductivity of air as a function of temperature is given by the relation:

$$k_T = 0.0129[717/(T + 225)](T/492)^{3/2} \tag{5}$$

in which T is in °F absolute.

While the width of the air space will not appreciably affect the heat transmission through it, the thickness of the materials used as insulating layers have quite a bearing on their heat insulating properties. This is illustrated in Fig. 47 which shows the conductance of "K" Felt as a function of its thickness.[5]

The table following gives typical heat-transfer coefficients for some materials affecting aircraft insulation.

K FACTORS (in btu/hr/ft²/°F/in.) FOR VARIOUS AIRCRAFT MATERIALS

Material	Weight/ft³	*K*
Aluminum		1400
Asbestos	loose	1.11
Balsa Wood	7.3 lb	0.33
Cork	5.4 lb	0.25
Cork Board	7.0 lb	0.27
Cotton Wool	loose	0.12
Dry Zero		0.24
Fiberglas	accdg. to dens.	0.24 to 0.28
Kapok Felt		0.21
Plexiglas		1.74 to 2.32
Seapak	Type C	0.22
Steel		312

In calculating the heat transmission through the plane outline it is important to treat all those panels and sections separately which have different overall heat transfer coefficients. For instance, the heat transmission through a plexiglass window is entirely different from that of the enclosing area which may be very well heat-insulated. In compartment-type planes it is usually advisable to calculate the heat loss for each individual compartment, and to treat the ceiling, walls and floors separately.

The total heat loss of the airplane is then:

$$H\ (\text{btu/hr}) = H_v + H_t \tag{6}$$

in which: $H_t = H_{t1} + H_{t2} + H_{t3} + \cdots$

and H_{t_1}, H_{t_2} etc. are the heat losses through the individual panels.

The final value thus obtained should be increased by about 10% in order to allow for a safe margin and the selection of standard capacities for the heating plant. This will also compensate for the uncertain factor of infiltration and for moderate changes of some coefficients with temperature, density and humidity which have been disregarded before.

The design of the cabin insulation is, primarily, based on considerations of soundproofing and will be discussed in the chapter dealing with that subject.

3.3 SUPERCHARGING. In the adiabatic compression which takes place in supercharging, a certain amount of energy is expended to compress the air from its outside pressure to the one desired within the cabin. Since, in this process, the volume remains constant, the expended energy results in heating of the compressed air.

The final temperature is given by the formula:

$$T_2\ (°\text{F abs.}) = T_1 \times (p_2/p_1)^{0.283}\ \text{(for single stage compression)} \tag{7}$$

The temperature increase of the air may be such that it suffices to offset the heat losses, particularly if the cabin is well sealed and insulated which is usually the case with supercharged planes. It is, nevertheless, necessary to calculate the heat thus generated as well as the heat requirements, and check whether they balance under all conditions. If this is not the case, a heater has to be installed with a capacity sufficient to make up the difference between the total heat loss and the heat supplied by the compression of the ventilating air. It must be borne in mind also that this heat can be counted on only while the supercharger is in operation.

4.0 Heat Requirements for Accessories

There are no general rules for the heating of aircraft accessories, since both the nature and conditions under which they have to operate vary extensively.

The heat requirements of a device depend as a whole, on its mass, the temperature at which it has to be kept, the temperature to which it is exposed and its qualities of heat absorption or radiation. Whenever possible, equipment which does not operate properly below certain temperatures, should be installed in a place where it is well

protected from the air stream and close to, if not within, heated spaces. However, guns and similar devices are usually fully exposed and often require considerable amounts of heat.

The two most-favored methods for the heating of accessories are electric heating and blast-heating. In the former, the device is covered by a shoe or envelope, consisting of heat-resisting and insulating material which is interwoven with numerous, fine, heating wires. Since the generated heat is very well preserved, small amounts of current suffice to obtain the desired heating effect. For instance, less than 200 watts are ample to heat the breech of a 50-calibre gun. This corresponds to only about 680 btu/hr while, in blast-heating, approximately 10 stu are needed to obtain the same result.

The electric energy for heating medium-sized accessories ranges from 100 to 500 watts, depending on the variables mentioned above.

Blast-heating is effected by means of hot-air blasts which are directed against the device to be heated. Since the temperature of the air stream should not be too high nor the air stream too concentrated, much of the heat is lost to the surrounding atmosphere or structure without directly benefiting the accessory, although heating of a relatively little exposed air space is desirable for both the equipment contained within this space and its operator, if he is stationed near-by.

A fairly accurate guide for the calculation of heat requirements of massive accessories such as guns is furnished by the following formula:

$$Q = (t_2 - t_1)(w_a c_a + w_b c_b + \cdots) \tag{8}$$

in which:

t_2 = Desired temperature of accessory, in °F;
t_1 = D.O.A.T., in °F;
w_a, w_b etc. = Total weight of individual materials used in accessory, in lb;
c_a, c_b etc. = Specific heats of respective materials.

The individual specific heats may be assumed to be constant. The value Q is then the total amount of heat in btu required to raise the temperature of a device from t_1 to t_2. If the process of heating to the desired temperature is permitted to take exactly one hour,

$$Q = H, \text{ in btu/hr}$$

Ordinarily, faster heating is necessary, and then:

$$H = Q\ 60/x$$

in which x is the number of minutes allotted to the heating process. Since H is the maximum heat quantity to be supplied at any time, it can usually be decreased after the device has been brought to the required temperature, as it then has merely to balance the heat losses caused by radiation and convection. If the temperature ranges are critical, such adjustments should be made by means of a thermostatic control.

The efficiency of blast-heating is quite low and depends mostly on the location of the heated accessory. If it is fully exposed to the cold-air stream, only a small percentage of the emitted heat will actually serve it. If it is located in a fairly well-enclosed space, the efficiency is correspondingly greater. A small amount of heat-proofing of such spaces will prove very helpful in this respect. As a rule, the capacity of the heater should be at least twice the calculated quantity.

When blast-heating is employed, great care must be taken to compensate for decreasing air densities at altitude as, otherwise, the temperature of the air blast might become too high. For this reason, calculations for heat quantities must be based on sea level conditions and air quantities increased for increase in altitude as shown in Fig. 43.

Experience has proven that from 10 to 20 stu are required for the heating of accessories by means of blast-heating. The choice between the lower and higher values depends again on such factors as service ceiling, air speeds, nature and location of the accessory.

5.0 HEAT REQUIREMENTS FOR MISCELLANEOUS EQUIPMENT

The methods of calculating or selecting heat quantities for miscellaneous equipment are quite similar to the ones discussed above. However, if electric current is available and the equipment is at all suitable for electric heating, it should always be given preference.

Electric heating is, for instance, very practical for the heating of water and other galley equipment. The normal wattage for electric immersion heaters in insulated storage tanks, equipped with thermostat, is about 250 watts. Coffee makers usually consume from 300 to 400 watts, while hot plates for the preparation of warm meals require about 600 watts.

If the heat requirements for the galley must be met by means other than electricity but are specified in watts, the values in watts are converted to btu/hr as follows:

$$H = w \times 3.415/e \qquad (9)$$

in which:

H = Heat load, in btu/hr
w = Wattage of comparable electric heater;
3.415 = Conversion factor;
e = Efficiency of heat transfer

The efficiency of the heat transfer must take into account the losses encountered in the ducts or pipes leading from the heater outlet to the galley accessory and the efficiency of the transfer itself. The value for e is usually about 0.5.

6.0 HEAT REQUIREMENTS FOR ANTI-FROSTING

Anti-frosting, that is the method of preventing the formation of condensation on the inside and ice on the outside of transparent surfaces by means of heat, is relatively new. For this reason, there are very few conclusive data and test reports available which permit the establishment of a proven method of calculating heat requirements for this purpose.

There seems to be, however, general agreement on the most desirable range of temperatures for the hot air streams used in such a method. This range is from 160° to 170°, with 165° as an acceptable average. Results show that an air stream at this temperature, if directed toward the inside of a window or windshield, will effectively prevent ice from forming on the outside.

In order to calculate the heat requirements, it is necessary to know not only the temperature of the air stream but also its rate of flow or quantity. It is true that the motion of warm air over the window surface in itself prevents moisture from condensing on it, as long as the impact is strong enough to remove the thin layer of cold air on the surface. Therefore, perpendicular flow against the window has been quite successful while tangential flow has not been very satisfactory inasmuch as it permits the existence of the cold film which, in turn, encourages condensation.

For the removal of ice which has formed on the outside or to prevent it from forming altogether, it is not sufficient to supply an arbitrary amount of warm air to the inside surface, and merely control its temperature to remain constant at around 165°. The problem is to find a simple method of computing the necessary heat quantities and, from those, the amount of air at 165° needed to transfer this heat to the window.

The required heat quantities depend on a great many factors such as the location of the window, air speed of the plane, atmospheric conditions and many others. The *double pane* installation on the windshields of United Air Lines Mainliners[6] required 1852 btu/hr/sq ft during tests to prevent frosting at 19°. As a rule, it appears that from 1 to 2 stu/sq ft should suffice in most cases, depending on the location of the window. However, there are several ways of calculating these requirements more accurately.

The most logical method of approach is to consider the window as a plate which is heated on one side and cooled on the other. A certain amount of heat is transmitted from the warm plate to the cold outside air and must be replaced by supplying an at least equal amount of heat from within in order to keep the temperature of the window from falling below the safe level. This amount is computed from formula (3), namely:

$$H_f = A \times (t_2 - t_1) \times U$$

in which:

H_f = Heat transmitted through window, in btu/hr
A = Area of window, in sq ft
t_2 = Cabin temperature, in °F
t_1 = D.O.A.T., in °F
U = Overall heat transfer coefficient, in btu/hr/ft²/°F

U is found by formula (4). The inside and outside film coefficients can be determined from the curve in Fig. 44. As the velocity of the warm air stream along the inside surface of the window may be quite high and thus become an important factor in establishing the inside coefficient, it should not be neglected.

Once H_f is known, the necessary air quantity can be calculated from formula (1). This calculation must be made for sea-level conditions, as explained before, and t_2 inserted as 165°.

At greater altitudes, the air quantity is to be increased at the rate shown in Fig. 43 so as to keep its temperature at 165°. However, in planes with low service ceilings, it is permissible to start with somewhat lower temperatures at sea level and go to slightly higher temperatures at the ceiling, without changing the air flow.

Ordinarily, the heat quantities thus established need not be added to the load of the heating system, since they are part of and contribute to the cabin-heating scheme.

The above methods of calculation will yield fairly acceptable results for comparatively large areas such as those of windows, portholes and windshields. Anti-frosting of sights and lenses is somewhat more complicated, due to their small size, sensitivity to temperature changes, mounting and location. In many instances, the entire equipment is heated so that the lens is kept in warm surroundings. However, if it is exposed to a cold air stream, separate heating is usually unavoidable. Electric heating is again preferable to blast heating since it is more efficient and easier to incorporate in devices of this type, apart from the fact that a sharply concentrated blast of warm air may harm the rest of the equipment and cause discomfort to the operator.

Heat quantities required for anti-frosting of sights or lenses are quite small and range around 100 btu/hr for blast-heating, and about

25 watts for electric heating, depending on the size, mass, installation and location of the lens.

7.0 Heat Requirements for Anti-Icing

As in anti-frosting, both the experiences and opinions vary as to the best method of calculating heat requirements for anti-icing purposes. The most important data in this respect have been obtained by a special staff of the N.A.C.A. during several years of intensive study but are of a confidential nature and not yet released for publication.

In a simplified method of calculating the approximate values required for the anti-icing of an airfoil, it is again feasible to consider the airfoil as a heated object which is being cooled by an air stream passing over its surfaces. This process results in the transmission of heat from the foil which must be balanced by providing an equal amount of heat from within. Accordingly, formula (3) should be used once more.

Assuming an air speed of 200 mph, and an average velocity of the warm air through the duct in the wing of about 2000 fpm, Fig. 44 shows $f_o = 46.5$ and $f_i = 7$. Therefore:

$$1/U = 1/7 + 1/46.5 + x_a/k_a$$

Inasmuch as k_a, the conductivity of the aluminum skin, is very high and the thickness of the metal very small, the value x_a/k_a can be neglected.

Thus: $U = 6.08$ btu/hr/ft²°F
and: $H_i = A \times (t_2 - t_1) \times 6.08$
in which: H_i = Heat amount required for anti-icing in btu/hr
A = Anti-icing area, in sq ft
t_2 = Mean temperature in anti-icing space
t_1 = Outside temperature
t_2 may be assumed as 200° and t_1 shall be −40°. Then:
$H_i = A \times 1460$ btu/hr

In other words, 1460 btu/hr must be supplied per square foot of anti-icing area under the above conditions. The anti-icing area usually extends from the leading edge of the wing to the front spar as shown in a sketch of the anti-icing installation of a Consolidated-Vultee "Catalina."[7]

The air quantities required for the transfer of these heat amounts can again be found by formula (1). A simplified method for the calculation of air quantities can be employed, if the loss and supply of heat are balanced, and the temperature differential does not change, as is the case here. Then:

$$H = 60 \times c \times d_a \times q_a \times (t_2 - t_1) = A \times U \times (t_2 - t_1)$$

hence

$$q_a = \frac{A \times U}{14.4 \times d_a} \qquad (10)$$

in which q_a and d_a represent the air quantity and density, respectively, at any particular altitude.

Regulation of the air flow for change in air density may not be necessary, if the service ceiling of the plane is low enough to keep the change of temperatures within permissible limits.

Methods for anti-icing will be discussed in a following chapter.

8.0 HEAT REQUIREMENTS FOR GROUND HEATING

Heat losses on the ground are usually considerably smaller than those during flight. There is not only less of a temperature differential, since the D.O.A.T. is higher and the specified cabin and equipment temperature lower, but U becomes much smaller due to the fact that the air speed is, at the most, that of the ground wind to which the plane is exposed.

Consequently, the output of the heating plant can be decreased which represents a very desirable saving in fuel and electric current consumption as ground heaters for this purpose are commonly of the internal-combustion type.

Heat and air quantities required to keep the cabin interior at a specified temperature are calculated by means of equations (1), (3) and (10). The heat needed to prevent the accumulation of snow and ice on wings, control and transparent surfaces is computed in a manner identical to the one used for flight conditions, with the exception that the values for the surface heat transfer coefficients f_i and f_o are selected in accordance with the respective air speeds on the ground.

If the velocity of the ground wind is low, heat loss due to radiation cannot be wholly neglected, particularly for black bodies, oxidized metals and the like. This loss can be computed by the following equation:

$$H_r = 0.172 \times p \times A \times (T_2^4 - T_1^4) \times 10^{-8} \qquad (11)$$

in which H_r = total heat radiated in btu/hr throughout the solid angle of 2π above the radiating surface;

p = emissivity of the surface

A = area of the radiating surface, in ft²

T_2 = temperature of the radiating surface, in °F absolute

T_1 = temperature of the surrounding air, in °F absolute

The emissivity is the ratio of the radiating power of the body to that of a black body of the same temperature. It varies with temperature, its degree of roughness and, if a metal, its degree of oxidation.[3]

Ground pre-heating requirements of accessories can usually be calculated by equation (8). This equation is also used to find the amount of heat needed to pre-heat an engine from a low ground temperature to a desired operating temperature. If the engine is well enclosed in a nacelle and kept at a specified temperature by means of warm air which is circulated through the nacelle, the necessary heat and air quantities can again be found by means of equations (1), (3) and (10).

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[3] Lionel S. Marks, *Mechanical Engineers' Handbook*, Third Edition.

[4] F. B. Rowley and A. B. Algren, "Thermal Resistance of Air Spaces," *A.S.H.V.E. Transactions*, Vol. 35, p. 165, 1929.

[5] *Data Sheet No. 3*, American Felt Company, October 1941.

[6] R. L. McBrien, "An Aircraft Double Windshield—Its Development and Use," *SAE Journal (Transactions)*, Vol. 51, No. 10.

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XIV

METHODS OF HEAT SUPPLY

1.0 Introduction

The development of aircraft heaters has moved rapidly during the past few years and the designer can now select from a group of well proven products a suitable heater for practically every requirement. Nevertheless, there is as yet no heater or heating system which can be recommended and used for all of the multiple applications on an airplane. The following chapters will, therefore, deal with various methods of heat supply.

There are three fundamental methods of heat supply of which the first is the simplest, the second the most logical and the third the most widely used. This contradictory statement will be understood shortly.

The first method is electric heating, the second, exhaust gas heating and, the third, internal combustion heating.

2.0 Electric Heating

One kilowatt of electric energy is equivalent to 3.415 stu of heat. Thus, an electric spot heater of 10 stu heating capacity would require about 3 kw. At the average airplane voltage of 24 V, this amounts to a current drain of 125 amp. Such current requirements are entirely out of the question, particularly, if heating capacities of 200 stu and more must be furnished for cabin heating alone. Therefore, completely electric heating cannot be seriously considered.

Nevertheless, electric heating is the simplest, safest and lightest method of heat supply and can be effectively employed where small heat capacities suffice. It requires only a small wire for connection instead of ducts or pipes. Its single control is a rheostat which permits regulation of the heat output over the entire range from "off" to maximum. Since the heat is produced at the point where it is needed and heat transfer is entirely eliminated, the efficiency of electric heating is higher than that of any other method known. It has no moving parts, entails little or no servicing, can be handled by anyone and is practically foolproof, even if damaged by enemy fire. It can be easily installed and is adaptable to almost every purpose.

The high current consumption of electric heating is the one and only factor which prevents its extended use on airplanes at this time.

There is little doubt, however, that once lighter and more efficient means have been developed to store or generate electricity, it will easily furnish the answer to most, if not all, heating problems. It is wise to keep the possibility of such a development in mind.

In spite of its limitations, electric heating is already used to some extent on many airplanes. The best known application is the electrically-heated flight gear such as manufactured by the General Electric Company. It consists of the heated suit shown in Fig. 48, which is actually an undersuit, heated shoes and heated gloves, illustrated in Fig. 49. Regular flying shoes are worn over the heated ones, and a light summer flying suit is worn over the electric suit, as demonstrated in Fig. 50. This photo also shows the control switch and regulating rheostat. Figure 51 lists the individual components of the complete gear.

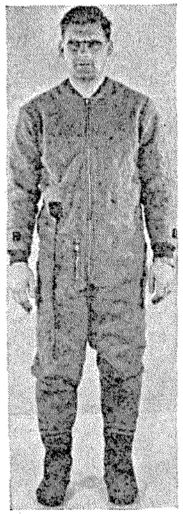

Fig. 48

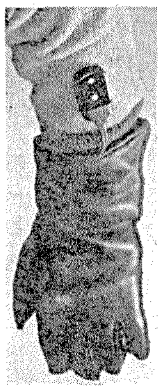

Fig. 49

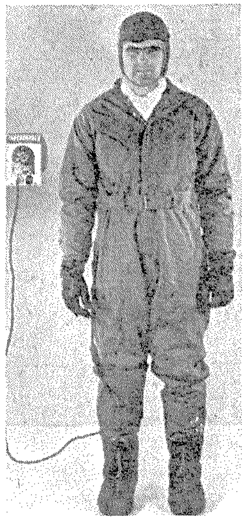

Fig. 50

Suit, gloves and shoes are made from a special, heat-resisting material which is provided with an interwoven net of hundreds of fine heating wires. All components are individually wired and controlled. Since the generated heat is applied directly to the body and its escape impeded, little current is needed. The entire equipment consumes only 375 watts which is less than 1.3 stu.

The following data, as supplied by the General Electric Company, emphasize the value of this method for cockpit heating. The John B.

Pierce Laboratories in New Haven conducted tests which indicated that, with the warmest unheated clothing available, the human trunk can be kept warm for only 2.7 hours at −30° and the extremities for 3.2 hours before reaching the danger point. At −45°, these figures are 2.3 and 2.8 hours. When properly worn, this electrically heated clothing assembly will keep the wearer comfortable at temperatures as low as −60°.

Pads and covers, similarly constructed, are used to advantage, if they can be wrapped around equipment and apparatus which, in conjunction with proper heat insulation, requires only little current to be kept at desired temperatures. Remember that less than 200 watts of electric heat, within a protective cover, will heat the gun-breech mechanism of a 50-calibre gun. Electric heating is also extensively used for the pitot-static tube of the air-speed indicator, water and galley heating, anti-frosting of lenses and many more.

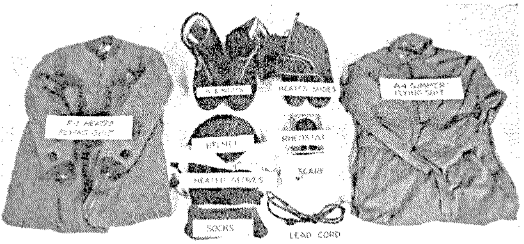

Fig. 51

Electric anti-frosting of larger areas such as those of windshields is still in an experimental stage. Brun[1] reports the results of tests made in France to heat windshields by means of an electrically heated screen inside the glass. He states that from 200 to 300 watts per 100 cm² of surface proved enough to free an iced-up windshield within two to three minutes, at an outside temperature of −10° C (+14° F) and an airspeed of 250 mph. This would correspond to about 2.2 to 3.3 kw per sq ft which, if these figures are representative, is too high to be feasible.

Although electric anti-frosting and anti-icing of small areas can now be accomplished by means of standard electric aircraft heaters which have outputs ranging from 0.6 to 6.0 stu, this method is usually not practical where larger heat outputs are involved. One of the few successful exceptions is the recent development of electrically conductive rubber covers for the anti-icing of propellers which, however, requires a separate source of current supply.

3.0 Exhaust-Gas Heating

In looking for a source of heat supply the thoughts of the designer will turn first to the vast quantities which are available in the engine exhaust. Figure 52 shows the total heat energy contained in the fuel which must be supplied to obtain a given brake horsepower output of the engine, and the heat lost through the exhaust which amounts to about 32%.[2]

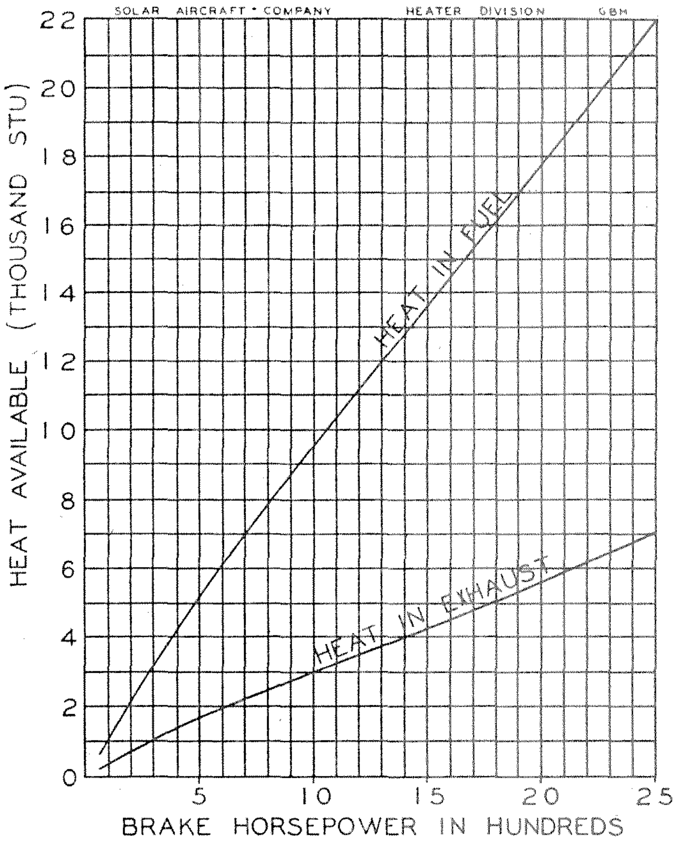

Fig. 52

As can be seen, a fairly-sized aircraft engine will produce exhaust gases which contain several thousand stu of heat energy. Even if only a fraction of this amount could be recovered and utilized, it would more than suffice to take care of all heating needs of the largest airplane.

The problem of efficient recovery is the main obstacle in employing this source of heat. However, during the past year, a number of designs have come on the market which show much promise. They permit the recovery of great heat quantities with comparatively little weight and space, and comply very well with the numerous other requirements of satisfactory heat exchange which are as follows:

1. The device for heat recovery (*heat exchanger*) must be sturdy enough to withstand all external and internal stresses, yet should be light and weigh not more than one pound for each 10 stu of rated capacity.
2. It must be small enough to fit into the available space, without requiring change of the conventional nacelle structure nor unreasonable rearrangement of engine accessories.
3. It should have no moving parts, with exception of air and mixing controls, and be safe and simple to operate.
4. It should not be affected by the large temperature differentials nor the components of the gases to which it is exposed, and should readily withstand attacks by lead, salt water and similar substances. Service should not be necessary before 100 hours of continuous operation and, if required, avoid the need for major disassemblies.
5. It should minimize the danger of CO infiltration into the ventilating air, not only under normal operating conditions but also, if damaged accidentally or by enemy fire.
6. It should not obstruct the passage of the exhaust products to any appreciable extent. The increase in back pressure due to the insertion of a heat exchanger should not amount to more than 1.5″ H_2O for every 100 stu.
7. The pressure drop of the ventilating air across the heat exchanger should not be greater than 1″ H_2O for every 1000 lb of air per hour.
8. No damage should result to the exhaust pipe, if the flow of ventilating air is reduced or even stopped completely.
9. If flame dampening is specified, the heater should readily fit into a suitable combination for this purpose.

As can be seen from the above, general requirements, the design of a satisfactory heat transfer unit is a very difficult one. This explains the fact that, heretofore, such units were used only when no other practical source of heat could be found.

The development of exhaust gas heat exchangers has been particularly stimulated by the urgent need for the large heat quantities used in anti-icing, anti-frosting, heating of accessories and cabin heating at very low temperatures. Indications are that exhaust gas heating will be selected for a growing number of installations and it is, therefore, necessary to discuss this subject in somewhat greater detail.

There are three commonly used methods of transferring the heat recovered in the exhaust to the place where it is to be used. The basic difference between these methods lies in the medium employed for transfer which may be either air, steam or a non-boiling liquid. The first type is called *Exhaust Air Heater,* the second *Exhaust Steam Heater* and, the third, *Exhaust Liquid Heater.* The difference in transfer medium results in fundamental differences of characteristics, application and operation although the source of heat is the same in all cases.

3.1 EXHAUST-AIR HEATERS have the following advantages: (a) They do not require any additional fuel or other means of generating heat; they utilize heat already existent which would be wasted otherwise. (b) They do not depend on any other medium, gaseous or liquid, with the exception of air. (c) They have no moving parts, thus simplifying operation and service. (d) They can furnish any heat quantities which may be needed, no matter how high they are. (e) Their control is simple, and only little auxiliary equipment is needed for this purpose.

Another advantage which, sometimes, is claimed for the exhaust heat exchanger is the fact that a considerable amount of heat is withdrawn from the exhaust gases and that, therefore, not only their temperature but also their volume is reduced. This, in turn, is said to assist in solving the difficult problem of finding more satisfactory materials for exhaust pipes, minimize after-burning and permit smaller pipe diameters beyond the heat exchanger, thus decreasing weight. However, the reduction of temperature and volume are of consequence only if the percentage of heat salvage is very high and, at any rate, higher than can be obtained with present models. This can be readily seen from the following example:

A heat exchanger with 250 stu capacity has been inserted into the exhaust of a 1200 hp engine. The exhaust pipe is 8″ in diameter, and the temperature of the exhaust gases, at full hp output, 1450°. According to Fig. 52, about 3,500 stu of heat energy are available in the exhaust of which 250 stu or 7.15% are being recovered. Assuming, for the sake of simplicity, that all other factors remain unchanged, then:

$$H_1/H_2 = T_1/T_2$$

in which the suffixes 1 and 2 denote the condition of the gas before and after heat extraction has taken place, H represents the heat amounts in stu and T the absolute temperature in °F.

$$T_1 = 1910$$

so that $T_2 = T_1 \times 92.85/100 = 1770$

and: $t_2 = 1310°\text{F}$

Thus, the temperature reduction is only 140° which is too little to be of any advantage. The tensile strength of the steel alloys employed in the manufacture of exhaust systems decreases quite rapidly at temperatures above 900°. Therefore, a temperature reduction of the order shown above cannot contribute anything toward the material problem, nor is it sufficient to assist in the prevention of after-burning.

This phenomenon, which is particularly annoying in night bombing, is mainly due to the presence of carbon monoxide in the exhaust gas. As it leaves the tailpipe and mixes with the outside air, it forms a combustible mixture. Although the temperature of this mixture may be below that required for ignition—which is about 1200°—the unmixed gases at the mouth of the tailpipe are hot enough to serve as igniting medium for the gas-air mixture ahead of them. As a consequence, flames appear to shoot out of the exhaust which are the more violent, the more incomplete the combustion and the greater the percentage of CO in the exhaust. In order to avoid the need for flame dampeners by merely cooling the exhaust gases, the temperature reduction caused by the heat exchanger must again be much greater than shown.

As far as the decrease of the gas volume from V_1 to V_2 is concerned, an approximate value is furnished by the following relationship:

$$V_1/V_2 = T_1/T_2$$

Thus, the reduction in the absolute temperature of 7.15% will result in a similar reduction of the volume and, consequently, of the cross-sectional area A of the tailpipe. Therefore:

$$A_2 = A_1 \times 92.85/100 = 46.5 \text{ in}^2$$

and: $d_2 = 7.7''$

This example proves that a heat extraction of as much as 250 stu would permit a reduction of even less than 4% of the tailpipe diameter d. Of course, once heat exchangers are produced which utilize a considerable portion of the heat available in the exhaust, the ensuing reductions of temperature and volume will undoubtedly become a feature of major importance.

Against these advantages are a number of disadvantages of which the following are the most pertinent:

a. In order to transfer a required amount of heat from one medium to another, a certain amount of common, metallic surface is necessary which, as will be shown in a following chapter, may be quite large, even if high velocities are employed for an optimum rate of heat transfer. This may entail requirements for weight and space which

can easily become prohibitive. However, accurate calculations and good design will assist in greatly reducing these factors.

b. The need for passing the exhaust gases along a heat transfer surface of sufficient area and possible diversion from their straight path increases the back pressure in the exhaust and thus reduces the efficiency of the engine. Proper design can again hold the increase in back pressure to a minimum.

c. The above is also true for the pressure drop of the ventilating air across the heat exchanger. Poor design will result in considerable drops and require either larger blowers or scoops.

d. Since the ventilating air and the exhaust gas are separated merely by a sheet of metal, there is the danger that cracks or bullet holes in the heat-transfer surface might permit the mixing of the air with the exhaust gases. The high content of carbon monoxide in the gas would then contaminate the ventilating air sufficiently to raise the percentage of CO quickly above the danger point.

Actually, there is little that can be done to eliminate this danger altogether. Among the suggestions to at least minimize it, is the use of double heat exchangers in which heat is transferred, at first, from the exhaust gas to intermediate air and, from this air, to the ventilating air. Thus, if one of the two heat exchangers has been damaged, there still would be no mixing of exhaust gas with the ventilating air. Although this scheme reduces the danger of carbon monoxide infiltration greatly, it is not very practical since it results in far greater weight and space, and much lower overall efficiency of heat transfer.

Neither would it be feasible to armor the heat exchanger as this would again increase the weight of the unit and merely protect it against shell splinters but not heavy calibre bullets nor accidental damage inside the unit.

The best method of increasing the safety of operation is to use means which indicate when and if the heat exchanger has been damaged and CO infiltration takes place. A number of instruments has been developed for this purpose but no method has yet been released which is entirely satisfactory. Most systems known so far utilize the chemical changes brought about by carbon monoxide on various materials to detect its presence. These changes may result either in discoloration, which can be registered visually or by means of a photo-electric cell, or in heating which can be detected by means of thermocouples.

The latter is the principle on which the Carbon Monoxide Indicator of the Mine Safety Appliance Company is based. This instrument has been used widely in mines and laboratories. A similar device had been installed on the Pan American Clipper ships. It is comparatively heavy, and its mechanism rather complicated. In addition, it is not entirely suitable for constant sampling. Therefore, the use of this instrument on airplanes is quite limited but its principle interesting enough to warrant a brief description.

It consists, essentially, of an electrically driven pump which draws a sample of the cabin air into a cell where any CO that might be present is converted chemically into CO_2. Parallel courses in this cell are filled with an active chemical and an inactive pumice substance. The active material is a granular mixture of manganese dioxide and copper oxide which serves as a catalyst for the conversion reaction of CO to CO_2. A series of thermocouples measures the difference in temperature between the active and inactive parts of the cell, if a reaction takes place. This, in turn, unbalances a Wheatstone bridge and operates a *sensitrol relay* which can be used to shut off the supply of contaminated air, to open the fresh-air duct and to operate a warning signal.

e. The main disadvantage of the Exhaust Air Heater, which it shares with all other heaters depending on the operation of the engine, is the fact that it cannot be used for ground heating. It is, of course, possible to idle an engine during brief stop-overs or to confine ground operation of the heater to the engine warm-up period. However, this method is not feasible, if ground heating is required for any length of time and, in this case, other means of heat supply, either auxiliary or permanently installed, must be found.

In spite of these disadvantages, the Exhaust Air Heater is, to many designers, the logical answer to the problem of supplying large heat quantities during flight. From what is known, it is the principal method of heating employed by the Germans. In this country, it is rapidly gaining in popularity, after a period of comparative neglect, and most manufacturers of aircraft heating equipment are now including this type of heater in their line. For this reason, a following chapter will be devoted to it.

3.2 EXHAUST STEAM HEATER. One pound of water requires about 1000 btu to convert it to steam. By the same token, as this steam condenses, it liberates an equal amount of heat. Thus, the generation of steam at one point and its condensation at another is a very efficient means of heat transfer.

In aircraft heaters of the exhaust steam type this method is utilized by inserting boilers into the tailpipe and pumping small quantities of water into them. Since the boilers are fully exposed to the flow of the exhaust gas, their temperature is so high that the water immediately flashes into steam. The steam then flows into radiators where it condenses and thus liberates the heat taken from the exhaust gases to generate it. The condensate then returns to the boiler and the cycle is repeated.

The schematic arrangement of such a system is shown in Fig. 53 which illustrates the *Airmax* steam heater as originally developed by Boeing. Two boilers, arranged in series, are inserted into the exhaust stack. The steam generated and super-heated in the boilers travels through a sump and, from there, to one or more radiators located in the hot-air duct. The condensate which is formed in the radiators is then forced back into the boilers by means of a feed-water pump.

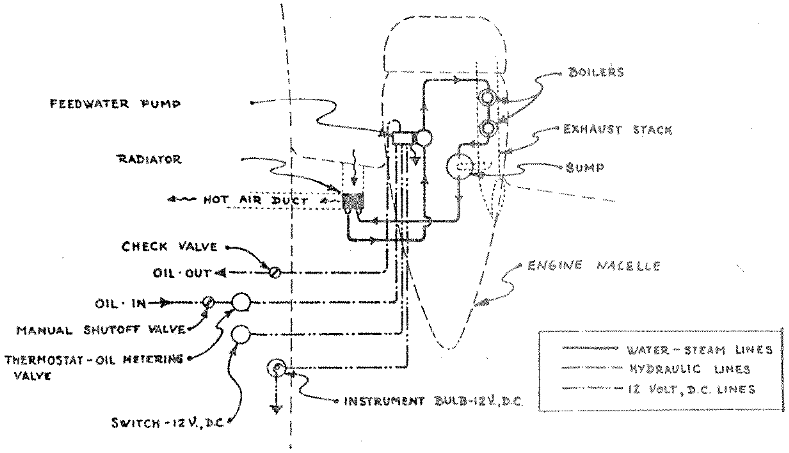

Fig. 53

The pump indicated in the sketch is hydraulically operated, and control of the heat output can be effected by regulation of the oil flow to the pump. Regulation may be both manual and automatic. The latter is taken care of by a thermostat operating an oil metering valve. Also provided are a master switch and an instrument bulb which is lighted when the system is in operation.

The exhaust steam heater shares many of the advantages and disadvantages of the exhaust air heater. Inasmuch as it utilizes the heat in the exhaust, it does not consume fuel or current for the supply of heat, however, it requires a small amount of water for the heat transfer. Since this water is being recirculated within the system and only little is lost, one pint of it may be sufficient.

The main advantage of the steam heater over the air heater is the fact that the danger of CO infiltration is practically eliminated. Furthermore, the small pipes carrying the steam or condensate can readily be employed for the heating of numerous accessories by coiling them around the object to be heated.

The major disadvantages of the steam system are the following:

Like the air heater, the steam heater cannot be operated on the ground unless the engine, in whose exhaust stack the boiler is located, can be idled. In addition, the steam system is inherently heavier than the air system for comparative heat outputs since some auxiliary equipment is required for its operation.

Although, theoretically, any amount of heat can be transferred in this manner, the heat output of steam heaters is limited by considerations of weight, space and back pressures in the exhaust. As a rule, about 150 stu capacity is their practical, upper limit per engine.

A frequent objection is the presence of steam lines inside the cabin. Particularly on military planes, damage to these lines and the subsequent escape of super-heated steam is a serious matter.

Another disadvantage of the exhaust steam heater is the service which it requires. For instance, if the plane is grounded for any length of time and at low temperatures, it is necessary to drain the water out of the system to prevent it from freezing and damaging the various components.

Among the methods used to eliminate the need for draining is the insertion of a sump which is located at the lowest point of the system so that the condensate will collect in it, if the heater is not in operation. Such a sump is shown in Fig. 54. It is designed to prevent bursting, if the water collected in it should freeze. Furthermore, it is provided with a connection to the exhaust stack so that the heat from the exhaust gases will melt whatever ice might have formed in it during stays on the ground. In spite of this provision, there will always be some water left within the system which, if frozen, will create pockets of ice and interfere with efficient operation for some time after the start, if not result in permanent damage.

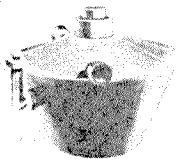

Fig. 54

Neither is it feasible to dilute the water with such anti-freezes as Glycol. If Glycol is present in steam, it will form droplets and thus still permit freezing of the condensate. Further data in this respect can be found in publications of the Carbide and Carbon Chemical Corporation.[3] For these reasons it is always advisable to provide for drain plugs at the low parts of the system and to drain the water completely after landing. While this service can be taken care of on commercial transports, military operations seldom, if ever, permit it. This factor must be taken into account on a military plane.

The greatest difficulties in the design and operation of steam heaters can be accredited to the high temperatures and pressures to which their individual components are exposed. Assuming an operating steam pressure of about 55 psi absolute for a 100 stu heater, and a head loss of 32 psi, the feedwater pump has to deliver a minimum output pressure of 87 psi absolute. Accordingly, the design pressure should be not less than 125 psi. The temperature of the steam under these conditions is in excess of 300°, and all parts including lines and fittings must be designed to withstand these pressures and temperatures under all operating conditions. This applies particularly to the boilers, feedwater pump and radiators.

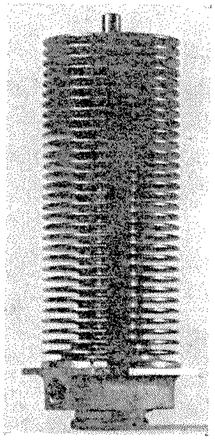

Fig. 55

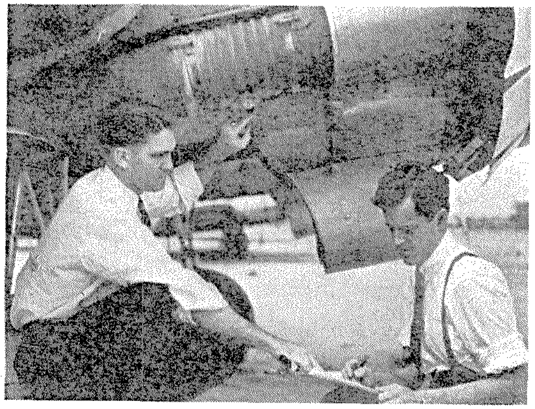

Fig. 56

3.21 *Boiler*—The weakest spot in a steam heater is usually the boiler. The dripping of water on the surface of the hot boiler amounts to a quenching action which severely stresses not only the body of the boiler but also the connecting welds and fittings. To cope with this condition the boiler used in the Airmax system shown in Fig. 55 was turned from a solid piece of titanium-stabilized steel. This boiler has a capacity of 40 stu, and as many as four may be used in series if the available space permits and the allowable increase of the back pressure in the exhaust pipe is not exceeded. It requires only 30 cu in of water (about one pint) for operation. Selection of suitable alloys and proper methods of fabrication can lengthen the life of such a boiler considerably. In spite of that, occasional replacements are necessary which, from a military point of view, are highly undesirable.

The boiler in the steam heater developed by the Douglas Aircraft Company consists of a row of nine parallel tubes, ½″ O.D. and 0.065″ wall thickness, which are also made from titanium-stabilized, stainless steel. The upper and lower ends of the tubes are welded into headers which, at the same time, serve as sumps.[4] Originally, the service life of this type of boiler was only 75 hours. However, due to improved welding methods, this has been extended to 450 hours, according to Douglas engineers. Installation of such a boiler on one of United Airlines' Mainliners is shown in Fig. 56. Although the tubes are arranged in a manner which will keep the increase of back pressure in the exhaust to a minimum, it is still higher than in a comparable, well-designed heater of the hot air type.

3.22 *Feedwater Pumps* present a further problem. Inasmuch as they circulate the water at near-boiling temperatures and must develop a considerable pressure, they will be a constant source of trouble unless properly designed and serviced. The pump may be driven either hydraulically or electrically. The hydraulic drive is often preferred because it eliminates the need for addition of another moving part as represented by an electric motor.

3.23 *Radiator*—The problem in designing a suitable radiator is to provide maximum effective surface at a minimum of weight and resistance to the air flow. The pressure drop of the ventilating air across the radiator should not exceed 3″ H_2O for each 100 stu of rated capacity which, incidentally, is considerably higher than that for a hot-air heater of similar capacity. On the other hand, it is necessary to employ high velocities in order to increase the rate of heat transfer in the radiator. Although velocities from 5000 to 6000 fpm are indicated, the ensuing air noise may be objectionable. At this speed, the heat transfer in the radiator will be about 20 btu/ft^2 of secondary surface/°F temperature differential/hr.[5]

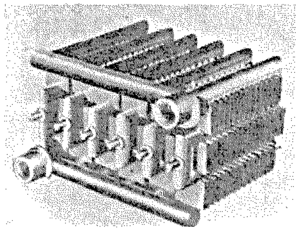

Fig. 57

The radiator shown in Fig. 57 weighs approximately 12 lb and has a capacity of 80 stu. An interesting installation is shown in Fig. 58. As can be seen, the radiator is inserted into the main air-intake duct and located in the floor of the flight deck.

This installation is similar to the one described in an article discussing the heating system of the Douglas DC-4.[6] Two independent systems are used which maintain a cabin temperature of 70° at an outside minimum of −40°. The radiators have about one square foot of face area and heat 200 cfm of air, delivering as much as 400 stu at sea level. Weight of both radiators together is 72 lb. Steam is supplied by two boilers which are located in the inboard exhaust, and weigh 45 lb each. Every unit requires 7 qt of water of which 4 qt are stored for reserve and not actually used in operation. Complete circulation takes place in one minute.

Another system worth mentioning is the *Galley* steam heating system which is used in England.[7] In this country, exhaust steam heaters are primarily used on transports, particularly on planes built by Boeing and Douglas.

Installation of steam-heating systems on small planes and, before all, those in military service, is usually not feasible for the reasons outlined above. In addition, many of these planes cannot provide the space for insertion of the boilers which would also result in unreasonable increases of the back pressures in the comparatively small exhaust stacks.

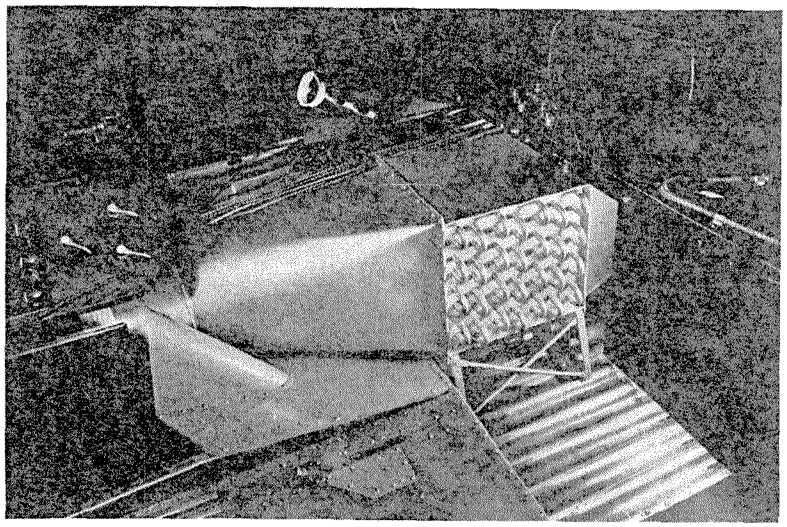

Fig. 58

3.3 EXHAUST LIQUID HEATERS are similar in principle to the exhaust steam heater with the exception that, instead of steam, a non-boiling liquid is employed for the transfer of heat from the exhaust pipe to the radiator. The advantage of this system over the steam heater is that both temperatures and pressures are considerably lower. On the other hand, the heat quantities thus transferred are rather small since they are limited to the heat which is consumed to raise the temperature of a unit weight of the transfer liquid from t_1 to t_2. Thus, the maximum heat quantity which can be transferred is:

$$H = w \times c \times (t_2 - t_1)$$

in which w is the rate of flow of the heat transfer medium through the radiator in lb/hr, and c its specific heat. In contrast, the heat transferred by steam includes the amount of heat required to change the water into steam of the same temperature which is about 1000 btu/lb water.

Therefore, a very high rate of circulation is required in the liquid heater to transfer even moderate heat quantities. This adds many new problems, especially in connection with proper sealing of joints and fittings.

Concerning the liquid employed for the heat transfer, the Aeronautical Recommended Practices of the S.A.E. suggest the following specifications.[8] The liquid must:

1. be non-inflammable;
2. have a boiling point of about 350°;
3. have a freezing point of about −60°;
4. be capable of being maintained at maximum temperature for prolonged periods without break-down;
5. be noncorrosive to steel, aluminum and aluminum alloys;

Obviously, the use of liquid heaters is limited. The main application is the heating of certain accessories on large planes and for such tasks as the heating of water and food. Liquid heating has also been suggested for anti-icing and anti-frosting. However, this is practical only where comparatively small areas are involved.

Most of the components used in liquid-type heaters are similar to those employed for steam heaters. The transfer liquid is, in practically all cases, Ethelyne Glycol.

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XV

INTERNAL-COMBUSTION HEATERS

The shortcomings of the previously described heating systems, and the rapidly growing and expanding needs of heat supply on airplanes made it necessary to explore new methods. This led the Stewart-Warner Corporation to adapt to aircraft heating the so-called *internal-combustion* principle, which had been very successful in their South Wind automobile heaters. Despite many added problems, this method proved so promising that it has been adopted by several other manufacturers and is now one of the most widely-used heating systems on American aircraft.

Instead of utilizing already existent heat, the internal-combustion heater generates its own supply by burning a mixture of air and fuel—normally aviation gasoline—within a combustion chamber. Ventilating air is forced over the hot combustion chamber and exhaust and thus heated. Like other systems, this method, too, has numerous advantages and disadvantages which must be carefully evaluated before deciding upon an internal-combustion heater for a particular installation.

1.0 Advantages

1.1 GROUND HEATING. The main advantage of this type of heater is that it is essentially independent from the operation of the airplane although, in some designs, certain connections to the engine are required which can be eliminated by the addition of auxiliary equipment. Self-contained, the heater will not only avoid the possibility of interfering with the engine but also will function both in the air and on the ground. This feature is of the greatest importance and is often the deciding factor in selecting an internal-combustion heater as it is the only permanently-installed type which provides ground heating.

1.2 WEIGHT-HEAT RATIO. Another advantage is the low weight to heat ratio which becomes still more favorable with increasing heat outputs. While, only a short while ago, these heaters weighed about one pound per stu, improvements during the past few years have decreased this ratio to as little as one pound per 10 stu.

1.3 HEAT CAPACITY which can be obtained is quite surprising and surpasses those of conventional exhaust air heaters. Outputs of 500 stu have been achieved with experimental units, and 300 to 400 stu are definitely practical.

1.4 APPLICATION. Being independent of location, and adaptable to most any required shape, these heaters can be placed where they serve their purpose best, without extensive ducting. This makes them suitable for the heating of the empennage and other portions of the plane to which heat from exhaust heaters could not be easily piped. Since they permit a great variety of combinations, they can be used for practically every application on an airplane.

1.5 FLEXIBILITY. Their control covers a wide range of heat outputs and can be either manual, full-automatic or both. The flexibility of the system is such that it may utilize some of the other components of the plane for operation or be wholly self-contained and portable, and operate even if it is entirely removed from the airplane.

2.0 DISADVANTAGES

2.1 FIRE HAZARD. One of the main objections to the use of internal-combustion heaters on aircraft is the presence of a fuel-burning unit within the fuselage. Any damage to this unit or its components might cause a fire in the cabin. This danger is even greater, if the fuel-air mixture is supplied by the engine carburetor—which is the case in some designs—and lines carrying this mixture pass through the cabin. It cannot be denied that such a danger exists, however, it is usually well taken care of by proper design and so minimized that it can be disregarded. Combustion chamber and other parts, enshrouding burning or hot gases, are made from carefully selected steel alloys which are thoroughly tested for all contingencies of operation, even under enemy fire. Furthermore, most heaters are provided with controls which will shut off the heater and fuel supply immediately, if the operation of the unit is affected in any way.

2.2 CARBON MONOXIDE. Still more objectionable than the presence of a burning fuel inside the cabin is the danger of carbon-monoxide infiltration in case the combustion chamber or exhaust pipe from the heater is damaged. This danger, too, can be minimized by suitable design of the heater and by keeping the length of the exhaust as short as possible. Further, it is advisable to install some type of carbon-monoxide control which will shut the heater off and permit the free circulation of fresh air in case an undue amount of CO should escape from the heater or heater exhaust. Realization of this danger has resulted in designs which all but eliminate it. However, these methods are not available for discussion at this time.

2.3 FUEL CONSUMPTION. A further disadvantage of the combustion heater is a direct consequence of the principle employed, namely the consumption of fuel. The data given for the heating value of aviation gasoline vary considerably and range from 19,000 to 21,000 btu/lb.

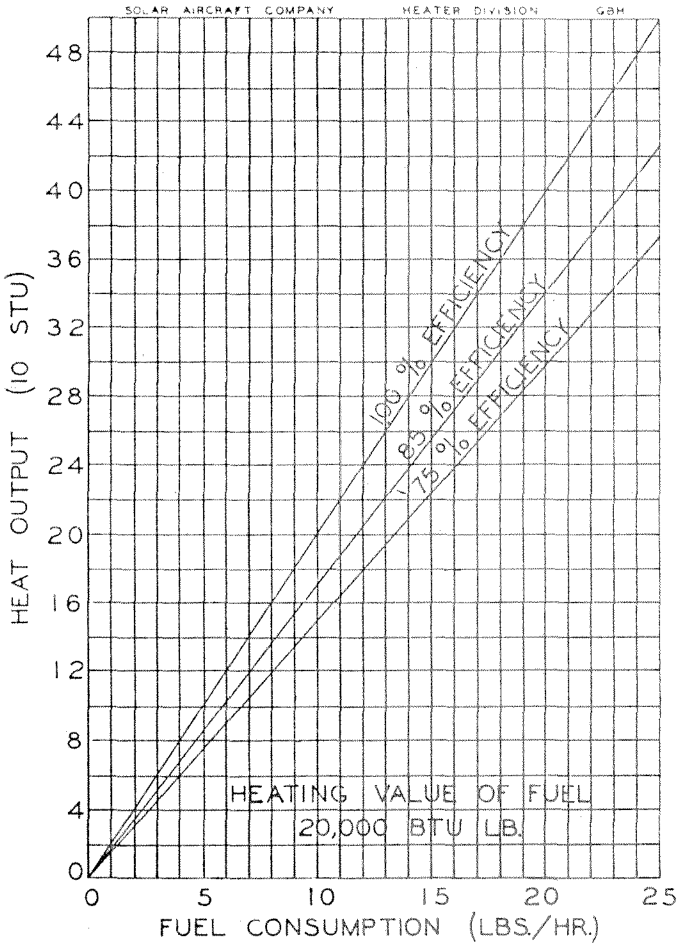

Fig. 59

A value of 20,000 btu/lb is, however, an acceptable average and well borne out by tests.

Assuming that a bomber is equipped with a combustion heater of 200 stu rated capacity, and that the heater is operated at full output and an overall efficiency of 85% for 8½ hours, then a total of 100 lb or over 16 gal of gasoline would be consumed. Considering the importance of every ounce of weight on an airplane, the addition of 100 lb for operation of the heater seems unreasonably high. On the other hand, landing gears or automatic pilot also contribute quite a bit of weight but are not omitted because they constitute accessories without which the plane is not fully operative. The weight expended for a heater and its fuel should be considered in the same light.

In addition, a heater is rarely operated at its maximum output during the entire flight, and the relative fuel consumption is usually a direct function of the size of an airplane. This is illustrated by the following example: A fighter is provided with a cockpit heater of 20 stu capacity which is operated at full heat output for one hour and at half output for two hours. At 85% efficiency, the total fuel consumed is only 0.39 gal or 2.35 lb. In both examples, the weight of the fuel consumed is a negligible percentage of the gross weight which is particularly true, if the overall efficiency of the heater is high.

The curves shown in Fig. 59 offer an interesting comparison of fuel weights required for given heat outputs at different heater efficiencies.

2.4 CONTROL. A common criticism in connection with early combustion heaters concerned their starting and control. Especially at high altitudes, ignition was difficult if not impossible; even on the ground it was frequently accompanied by a series of violent explosions. Control during and after starting consisted of a number of operations requiring time and skill.

This criticism does not apply to the models being manufactured now. Development of automatic controls for ignition and operation has all but eliminated the previously experienced difficulties.

2.5 ALTITUDE OPERATION. The foregoing is true for another problem: combustion air supply at high altitudes. This difficulty, too, can be considered eliminated; modern combustion heaters will operate at any altitude at which airplanes fly.

2.6 LEADING. Some difficulties are also encountered through accumulation of lead deposits which are formed during the combustion of leaded gasoline. As the lead particles are very small—only a few microns in diameter—they settle as a fine dust which, after a while, will begin to interfere with the proper operation of the heater. Although lead deposits can be removed easily, this is a service requirement which may be objectionable if it is too frequent. However, burner improvements have resulted in overcoming the interference of lead deposits so that no removal is required for at least 100 hours of continuous operation.

3.0 DESIGN CONSIDERATIONS

The internal-combustion heater consists, essentially, of the following components:

1. Means for supply of combustion air;
2. Means for supply of ventilating air;
3. Means for supply of fuel;
4. Means for ignition;
5. Combustion chamber;
6. Means for heat transfer;
7. Exhaust;
8. Housing;
9. Controls.

Proper design of these components is based on a number of considerations which are discussed below.

3.1 SUPPLY OF COMBUSTION AIR. The air weight required by internal-combustion heaters to burn a unit weight of gasoline is usually from 13.5 to 15 times that of the fuel as will be further analyzed in connection with combustion. Thus, a heater of 80 stu capacity which burns 4 lb/hr of fuel, would require at least 13.5 × 4, that is, 54 lb/hr of combustion air. At sea level, this amounts to:

$$54/(0.075 \times 60) = 12 \text{ cfm}$$

This volume is not very large but must be supplied at sufficient pressure to overcome the resistance in the system. The back pressure varies considerably for different types of heaters and, for 12 cfm, may range from 2″ to 6″ H_2O, depending mainly on the construction of the heat exchanger. However, 12 cfm at such pressures can be readily supplied by the ram during flight.

It shall be assumed now that this heater must function at an altitude of 35,000 ft at which the air density is about one third of that on the ground, or 0.025 lb/cu ft. In this case 3 × 12 = 36 cfm must be supplied in order to maintain the same mass flow of air. As shown in a previous chapter, this will increase the back pressure approximately in proportion with the increase in volume so that:

$$h_a = h_s \times V_a/V_s \tag{1}$$

in which the suffixes a and s again denote altitude and sea level, respectively, h the pressure in inches H_2O and V the volume in cfm. Thus, in the foregoing example:

$$h_a = 6 \times 36/12 = 18'' \ H_2O$$

In order to supply this amount and at this pressure, the speed of the plane cannot be too low or a blower must be used for the supply of the combustion air. This is unavoidable if the plane is to be heated on the ground.

As stated before, the horsepower required to drive a fan or blower is determined by the following formula:

$$P \text{ (in hp)} = K \times q \times h/33{,}000 \times e \qquad (2)$$

in which: $K = 5.2$
$q =$ air volume in cfm
$h =$ pressure, in inches H_2O
$e =$ efficiency of fan, which shall be assumed to be 0.65
Thus: $P_s = 5.2 \times 12 \times 6/(33{,}000 \times 0.65)$
and: $P_s = 0.0175$ hp or 13 watts

This low power requirement warrants examination of the feasibility of omitting the scoop altogether. In this case, the blower would have to be capable of delivering the air supply at the service ceiling of the plane which means increase in both volume and pressure. Then:

$P_a = 5.2 \times 36 \times 18/(33{,}000 \times 0.65)$
and: $P_a = 0.157$ hp or 117 watts.

Even this figure is not excessive and may induce the designer to supply the combustion air by means of an electrically driven fan both in the air and on the ground, and thus avoid a scoop. There is, however, one factor which should not be overlooked, and that is the need for supplying an added and larger amount of air for ventilation.

3.2 SUPPLY OF VENTILATING AIR. The problems involved in calculating the air quantities necessary to transfer a given amount of heat, at a specified temperature differential and density, have been discussed in Chapter XII. As will be remembered, these factors are connected by the following relationship:

$$H = 60 \times c \times q \times d \times \Delta t \qquad (3$$

Thus, if the heat output in btu/hr and the temperatures from and to which the ventilating air is to be heated are given, the necessary air quantity can be readily calculated. Since the value for d–the density of the air–is the highest for sea-level conditions, the maximum heat amount at constant volume is required for flight at minimum altitude although the temperature differential is somewhat smaller. This is quite obvious since at about 35,000 feet, the density is only one-third of that on the ground while the temperature differential increases by not more than a few per cent. For instance, the desired cabin temperature may be specified as 70° at all altitudes while the D.O.A.T. is $-60°$ on the ground and $-100°$ at the ceiling.

Then: $\Delta t_s = 130$
and: $\Delta t_a = 170$
Consequently: $\Delta t_a = \Delta t_s \times 1.3$
Since, $H_a = H_s \times d_a/d_s \times \Delta t_a/\Delta t_s \qquad (4)$
and, at 35,000 feet: $d_a = d_s/3$
$H_a = H_s \times 1/3 \times 1.3 = H_s \times 0.43$

Therefore, the heat quantities needed to keep a given volume of air at a specified temperature decrease with altitude, and the maximum capacities of heating plants must be based on sea-level conditions.

These considerations apply only for constant air volume. If, however, the mass flow of the air must be kept constant at all altitudes, calculations for air quantities must be made for conditions at maximum ceiling. Assuming that, for instance, a constant mass flow of 1000 lb/hr of air is specified, 13,350 cu ft/hr of air have to be supplied at sea level while 40,000 cu ft/hr are required at 35,000 ft.

If the mass flow is constant, heat requirements increase slightly with altitude since the temperature differential increases. By the same token, operation of the heater at maximum output will then result in higher cabin temperatures on the ground than at altitude.

Although these considerations are quite elementary, it is necessary to discuss them since their disregard has often resulted in impossible specifications and design. The main factor to remember is that all air passages, back pressures and other items concerning the supply of air for internal combustion heaters must be calculated for the mass flow at the service ceiling at which, for constant heat output, air volumes and resistance to their flow are the highest.

In calculating the ventilating air rate for the previous example, namely a heater of 80 stu capacity, and a temperature differential of 300°:

$$80{,}000 = 60 \times c \times q \times d \times 300$$

c is again assumed as 0.24 btu/lb/°F and thus:

$$q \times d = w = 18.5 \text{ lb/min or } 1110 \text{ lb/hr}$$

As this value must remain constant, 247 cfm of ventilating air have to be supplied at sea level to maintain the temperature differential of 300° across the heater while, at 35,000 feet, this quantity increases to three times that much, that is, 741 cfm.

It has been pointed out before that the pressure drop for ventilating air across a heat exchanger should not exceed 1″ H_2O for 1000 lb/hr of air flow. Assuming that, accordingly, the pressure drop of this heater is 1.2″ H_2O at sea level, its value at 35,000 feet for the identical mass flow would be:

$$h_a = h_s \times 3 = 3.6'' \text{ H}_2\text{O}$$

Now, if the ventilating air would have to be supplied by a blower, the power required to drive it at sea level would be, according to equation (2):

$$P_s = 5.2 \times 247 \times 1.2/(33{,}000 \times 0.65)$$

and: $$P_s = 0.072 \text{ hp or } 53.7 \text{ watts}$$

At the service ceiling, these values are:

$$P_a = 0.646 \text{ hp or } 482 \text{ watts}$$

Inasmuch as an 80 stu capacity heater would suffice as the sole source of heat supply only on a cabin plane and, if used on a larger plane, would furnish merely a fraction of all heat requirements, 482 watts for the supply of the ventilating air is rather high. In addition, the weight of a suitable motor and blower combination may be objectionable. Therefore, most designers hesitate to use blowers for this purpose unless ground heating is specified. Even in this case, a scoop may be used during flight instead of the blower in order to avoid excessive drain of electric current.

On the other hand, it is always advantageous to eliminate scoops, particularly on fast planes, because they add considerable drag and the ducting from a scoop to the heater or heaters is often more objectionable than the current consumption and weight of a blower.

The most desirable method of air supply differs for every installation and depends largely on such factors as wishes of the procuring agency, suitability of ducting, requirements of ground heating, availability of current, and reasons for or against the use of scoops. Since the supply of combustion air requires comparatively small quantities at high pressures while the ventilating air must be supplied in greater quantities but at low pressures, it is often feasible to separate the two supplies. Thus, the designer can choose between the following combinations:

a. Common scoop for combustion and ventilation;
b. Separate scoops for combustion and ventilation;
c. Blower for combustion, scoop for ventilation;
d. Scoop for combustion, blower for ventilation;
e. Common blower for flight and ground operation;
f. Common blower for ground operation only;
g. Separate blowers for flight and ground operation;
h. Separate blowers for ground operation only.

Usually, the choice of the most suitable combination is not difficult.

In some planes, there may be room for a scoop of sufficient size while the available ram pressure would be insufficient for the combustion air supply. This necessitates a small blower for the latter only. On other planes, there may be enough ram pressure but objections to a scoop large enough to take care of both ventilating and combustion air needs. This problem is solved by providing a scoop for the combustion air and a blower for ventilation.

On another plane again there may be no objections to the additional weight of a permanently installed blower but no electric current can be sacrificed to drive it. In this case a satisfactory installation would suggest the use of scoops in the air and blowers on the ground, with a small gasoline engine added to furnish the motive power.

Separate blowers are usually indicated in cases where a small, *Roots*-type blower is needed to furnish small quantities of combustion air against high back pressures while a squirrel-type blower, or coaxial fan, supplies the ventilating air.

3.3 FUEL SUPPLY. The fuel used in internal-combustion heaters is normally leaded aviation gasoline of 100-octane rating. There are some exceptions which, however, are not of major importance and will be discussed later.

Conventional methods of fuel supply fall into two classes. In the first, a fuel-air mixture is drawn from the carburetor of the engine. The advantage of this method is the elimination of additional means for combustion air supply and all of the problems connected with it. On the other hand, connections to the engines are not favored since any irregularity in the operation of the heater may affect the engine fuel supply. Furthermore, the presence of lines carrying a highly combustible mixture within the cabin is quite dangerous. Therefore, in selecting this method of fuel supply for a heater, it is necessary to weigh its simplicity against the hazards which it entails.

In the second method, the fuel is drawn directly from the fuel tanks of the airplane. This can again be accomplished in two ways, namely by gravity feed or by forced feed. If gravity feed is employed, the heater must be located enough below the tanks to obtain the necessary head for proper fuel flow unless the fuel is supplied under pressure from the tanks, which is not uncommon on large planes. In this case, a fuel pressure regulator should be inserted into the fuel line.

The advantage of forced feed is the independence of the heater from its location and from variations of fuel pressure in the tanks or supply lines. The pumps used for this purpose are either hydraulically or electrically driven. Electric pumps of the rotary type consume less than 1 amp of current and deliver up to 5 gal/hr at a pressure of several inches

Hg. Since their weight is small—about 2 lb—it is worth using such a pump to have the assurance of proper fuel flow. In addition, a rheostat inserted into the circuit of the series-wound motor permits convenient modulation and remote control of the fuel flow and thus, of the heat output.

Filters in the fuel line are always desirable and are essential if fuel injection is used instead of conventional carburetion. In the former, the fuel is injected into the combustion air stream through a fine nozzle which may be quickly closed by even minute particles and thus cut off the fuel supply.

The choice between carburetion and fuel injection should be left to the heater manufacturer. In the experience of the author, fuel injection is usually preferable as its permits better control of the fuel-air mixture, particularly at low temperatures and densities.

3.4 IGNITION. Opinions are sharply divided as to the best means of ignition in internal-combustion heaters. The more common method is to use one or two spark plugs in the combustion chamber which are excited in conventional manner by means of vibrator and coil. The main advantage of this system is the low current consumption and long life of plugs.

In the hot-wire method, ignition is effected by a wire loop or coil which is electrically heated above the ignition temperature of the fuel, usually to between 1300° and 1400°F. The advantages of this method are a larger ignition area, simplicity and smaller weight. In addition, it permits an instantaneous and positive control, if the ignition should fail.

With spark-plug ignition, failure may occur although the electric circuit is still intact, for instance, if the electrodes of the plug are covered by carbonized fuel so that no, or only irregular, sparks pass between them. This results in the accumulation of combustible mixture which, if finally ignited, will explode with possible damage to the heater.

Hot-wire ignition can fail only if the supply of electric current ceases —which would shut the entire heater off—or if the igniter wire burns out. In this case, a relay, in series with the igniter wire, can be used to shut off the fuel supply immediately. This safety feature is of great importance and speaks heavily in favor of hot-wire ignition.

The main disadvantages of this method are the relatively short life of the igniter wire and its current consumption. If the wire is exposed to the fuel-air stream, the cooling effect of the latter requires relatively large currents to keep the wire above the ignition temperature of the fuel and results in shorter life. However, if the wire is placed in a comparatively cool and draft-less part of the combustion chamber, it will be found that, while ignition is just as good or even more positive, not only smaller currents suffice but also that the wire lasts longer. Life can be further lengthened by placing shields, screens or baffles around the wire. Dependable ignition can thus be obtained with as little as 35 watts. An igniter of this type is shown in Fig. 59-A.

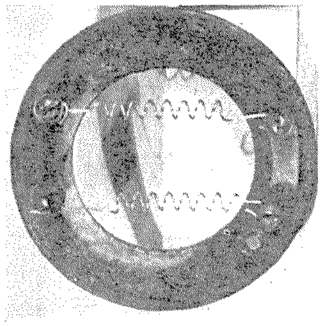

Fig. 59-A

Nichrome V wire appears to be best suited for this purpose. Experiments with platinum wires showed marked disintegration and quick burn-outs.

Another question to decide is whether the ignition should be kept on during the entire operation of the heater or turned off as soon as ignition has taken place. In the latter method, it is necessary to add a thermostat which means another service part which may fail. Apart from mechanical difficulties, thermostats for such applications are not always dependable and have a time lag which permits the accumulation of combustible mixture and subsequent explosions. On the other hand, permanent operation of the ignition entails a continuous current drain and greater wear but makes ignition simpler and more dependable.

3.5 COMBUSTION. In order to burn fuel, there must be a certain supply of oxygen. Since it is impractical to use pure oxygen, it is common practice to supply air in such quantities that the amount of oxygen contained in the air meets the combustion requirements of the fuel.

The weight of air necessary for the perfect combustion of a pound of fuel can be determined by the use of the ultimate analysis of the fuel and is then found by the following formula as given in the *Heating Ventilating Air Conditioning Guide* for solid and liquid fuels:

$$W = 34.56[C/3 + (H - O/8) + S/8] \qquad (5)$$

in which W is the air weight required for combustion of one pound of fuel, and C, H, O and S represent the percentages by weight of the elements designated by these symbols.

An approximate value of the theoretical air requirements for any fuel can be found by means of the following relation:

$$W = \frac{0.755 \times \text{Heating Value of Fuel in btu/lb}}{1000} \qquad (6)$$

Since the heating value of aviation gasoline is about 20,000 btu/lb equation (6), if applied to gasoline, yields:

$$W = 15.1$$

In other words, the theoretical, approximate fuel-air ratio for gasoline is about 1:15 which checks very well with empirical and calculated data. Ordinarily, somewhat richer mixtures are used for internal-combustion heaters, and a fuel-air ratio of 1:13.5 is quite common.

Actually, more air should be supplied for perfect combustion than the amount theoretically required. The difference between these two air amounts is called the "excess air." Thus the

$$\text{Percent Excess Air} = \frac{\text{Air Supplied} - \text{Theoretical Air}}{\text{Theoretical Air}} \qquad (7)$$

The *Heating Ventilating Air Conditioning Guide* gives the following equation to determine, with reasonable accuracy, the amount of air actually supplied for one pound of most solid and liquid fuels:

$$\text{lb dry air supplied per lb of fuel} = \frac{3.036\ N_2}{(CO_2 + CO)} \times C \qquad (8)$$

in which CO_2, CO and N_2 are percentages by volume from the flue gas analysis and C is the weight of carbon burned per pound of fuel, corrected for losses.

If the fuel-gas analysis is made by means of an Orsat apparatus, the following formula will be found to be quite useful and is also suggested by the *Heating Ventilating Air Conditioning Guide:*

$$\text{Percent excess air} = \frac{100(O_2 - CO/2)}{N_2 \times 0.264 - (O_2 - CO/2)} \qquad (9)$$

The importance of weight considerations on an airplane makes it mandatory that the efficiency of combustion in internal-combustion heaters is the highest possible. Therefore, the proper supply and regulation of combustion air must be closely checked during tests by means of the above methods.

A most difficult problem in this connection is the preservation of constant mass flow at all altitudes, as previously discussed. In some heaters, this problem is eliminated by drawing the fuel-air mixture from the engine carburetor in which case no further compensation is necessary. However, this scheme is not at all favored for the reasons outlined before.

In planes with low service ceilings it often suffices to use a conventional carburetor in the heater and adjust it for a lean mixture on the ground. As the plane ascends to greater altitudes, the mixture will become increasingly rich but still remain combustible although difficulties may be encountered with ignition.

If the plane has a service ceiling higher than 12,000 ft, means for regulation of mass flow must be provided. This can be accomplished by one of two systems, namely *positive* or *negative* supercharging.

In positive supercharging a blower supplies increasing quantities of combustion air as the plane ascends and delivers correspondingly more power to compensate for the greater back pressures. The regulating medium is usually a device containing sealed bellows which will expand with increasing altitude and operate either a rheostat in the blower circuit or a damper in the air duct. This method has not been found to be entirely satisfactory inasmuch as the action of the bellows is somewhat erratic and sluggish, and not entirely proportional to the air volumes required. Better results are obtained, if the combustion air is supplied by the cabin supercharger of the plane where such a scheme is possible.

Negative supercharging, as introduced by the author some years ago, is based on designing all components of air supply for the highest ceiling at which the heater is expected to function, taking into account both the volumes and pressures at that altitude. As the plane descends and the density of the supplied air increases, the excess air is bypassed and excess pressures throttled by means of automatic pressure and volume regulating devices. Practice has shown that this method of operation is quite effective and dependable, and that rather close control of constant mass flow can be obtained, even at very great altitudes.

If internal-combustion heaters are not provided with air-flow controls, the fuel-air mixture will become the richer the higher the altitude until combustion is no longer possible. Long before this point is reached it is difficult, and finally impossible, to ignite the heater.

Consequently, the *service ceiling* of a heater is the highest altitude at which the heater not only operates at its full, rated heat output but can also be readily ignited and re-ignited. The *absolute ceiling* then is the altitude at which even sustained combustion of the heater ceases for lack of oxygen.

3.6 HEAT TRANSFER. The efficiency of internal-combustion heaters is mainly determined by the efficiency of transferring the heat which is generated during the process of combustion, to the ventilating air.

Heat transfer may be accomplished in a number of ways which range from the use of small fans blowing air over the combustion chamber in low-capacity heaters to blowers forcing considerable quantities of air through and over large transfer surfaces in heaters with high outputs. In general, one of the following three methods is employed: (a) Air is blown over and along the combustion chamber which may be provided with fins or other means to increase its secondary surface; (b) Air is blown over and along the exhaust pipe which is arranged in banks and designed for a maximum of both primary and secondary surface; (c) The third method is a combination of the previous ones.

Ordinarily the latter method is favored since some cooling of the combustion chamber is always necessary in order to relieve thermal stresses, and the need for high efficiencies requires recovery of the heat in the exhaust gas.

The limitations imposed on heat transfer are due to considerations of weight and space, and the endeavor to keep the resistance to air flow in the combustion and ventilating air lines as low as possible. On the other hand, the conditions in the combustion circuit are somewhat more favorable than they are in an exhaust-gas heat exchanger. While, in the latter case, every inch of added resistance would decrease the efficiency of the airplane engine, no such problem exists in an internal-combustion heater. Therefore, somewhat higher back pressures are permissible although they should not be such as to aggravate the difficulties of combustion air supply, particularly at high altitudes. As a consequence, the efficiency of internal-combustion heaters is normally quite high and may reach 85% of the heat value of the fuel, with even higher percentages being claimed.

Design details of various heat transfer units as employed in internal-combustion heaters cannot be released for the present. However, their fundamental principles are similar to those of exhaust-gas heat exchangers which will be discussed, at greater length, in a following chapter.

3.7 EXHAUST. Most internal-combustion heaters use a closed combustion circuit in order to minimize the danger of CO contamination and fires within the cabin. This circuit begins with the intake scoop and ends with the exhaust spill, with no openings inside the cabin. While the piping and connections leading to the heater are not very critical, conditions for the exhaust are different since it carries gases which are not only very hot but also highly toxic.

It is necessary to keep that length of exhaust which is not needed for heat transfer as short as possible and to provide a small spill near the heater located in the skin where a negative pressure exists so that the exhaust gas is aided in its escape. Furthermore, precautions must be taken to prevent the return of the spilled gases into the cabin through adjacent cracks and openings, particularly if personnel is stationed nearby.

Serious thought must also be given to the possibility of damage to the exhaust line, caused either by wear, accident or enemy action. In one system this problem had been solved by inserting the blower into the exhaust side and using it as a pump rather than a blower, thus creating a negative pressure inside the pipe with respect to the outside atmosphere. However, this system has other disadvantages which more than offset this advantage, especially in connection with combustion at altitude.

Since carbon monoxide is odorless, the safest method to prevent its unnoticed escape from any of the heater components is to provide a CO indicator which will turn the heater off, if exhaust gas should leak into the cabin.

As a protection against the heat transmitted by the pipe it is advisible to cover it with a heat-insulating material. In spite of that, it should be kept at a reasonable distance from such devices or materials which may be affected by heat, and from accidental contact with personnel.

3.8 HOUSING. Due to the inherent dangers of internal combustion, particular attention must be given to the heater housing and the mounting of its components. Like all other aircraft accessories, the heater should be compact although every single part must be easily accessible. The occasional need for servicing, replacements and removal of lead deposits should not entail major disassemblies.

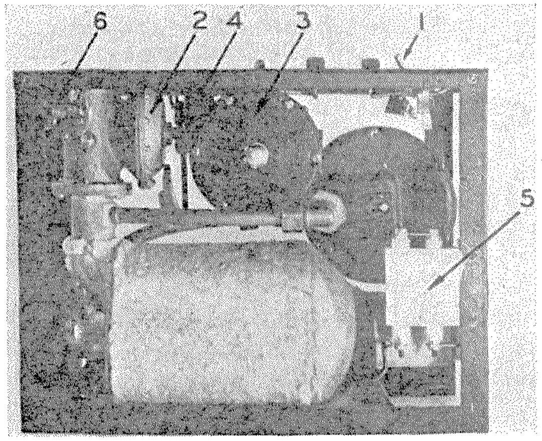

Fig. 60

At the same time, the construction and mounting of all parts, particularly the combustion chamber and controls, must be such as to withstand shock, vibrations and the gravitational forces encountered in flight. An example of such a construction is shown in Fig. 60 which represents the inside of a propane-fired Airmax Altiheater. As can be seen, all parts are fastened to a rigid frame which can be lifted out of the housing and is thus accessible from all sides.

One of the requirements of good heater design is that its housing can be so shaped as to fit into most any available space. Heaters over 80 stu capacity are usually cylindrical for this reason, as shown in the photographs on the following pages.

The practice of putting numerous meters, indicating devices and lights on the heater housing should be discouraged. In view of the fact that the flight crew has to watch already too great a number of instruments which are vital for the operation of the airplane, it would be unreasonable to expect that any time is left for scientific study of the heater performance. In the majority of cases the heater will be mounted in a location which does not permit observation of instruments anyway. Manual controls should not be mounted on the heater itself but should function by remote control. Neither is it necessary to provide instruments or warning signals which indicate failure. The controls should be automatic so that if anything goes wrong with the heater, fuel supply, air and ignition are immediately cut off. The simplest and most positive indication as to whether the heater is turned on and working satisfactorily, is the temperature within the cabin.

4.0 Controls

The controls of internal-combustion heaters and most other types of aircraft heaters can be divided into manual and automatic controls. The latter are designated as either *automatic, operating* or *automatic, safety* controls.

4.1 CONTROLS, MANUAL. The manual procedure required to start and operate internal-combustion heaters, up to a short time ago, was a rather complicated one and consisting of starting the blowers, ignition and the initial regulation of combustion separately. In the newer models, manual control is limited to a single lever or switch for both remote starting and modulation; even this operation may now be fully automatic. However, it is necessary to retain at least a manual master switch, preferably located in the flight deck, which can also serve as manual override in emergencies.

The need for simplifying control makes it desirable to eliminate modulating regulation in heaters below 12 stu capacity, and to use merely an *on-off* toggle switch such as denoted by (1) in Fig. 60. Heaters with larger capacities should have a modulating control which permits regulation from maximum heat output down to 20% of rated capacity.

If the heat output is controlled by means of a rheostat in the circuit of a fuel-pump motor, it is required to have the following series of positions: Off–High–Low, since a high impulse is needed to overcome the initial inertia of the pump and motor after turning the heater on. The disadvantage of this arrangement is that it makes automatic proportioning control somewhat more complicated inasmuch as such controls tend to modulate from high to low to the off position and vice versa.

4.2 CONTROLS, AUTOMATIC, OPERATING. The main objection to automatic controls in aircraft heaters is the problem of their dependability. Both in the case of automatic operating and safety controls, failure of the one or the other may have serious consequences. On the other hand, a certain amount of automatic control is essential to make the operation of the heater simple and safe.

4.21 *Modulating Control*—Most important of the automatic operating controls is the one for modulation of the heat output. It may be one of the following:

4.211 *On-off Control*—This control is operated by a thermostat which starts the heater, if the ambient temperature drops below a pre-adjusted minimum, and shuts the heater off, if the temperature reaches a likewise pre-adjusted maximum. The differential between the maximum and minimum positions is determined by the sensitivity of the thermostat. This control is used mainly for heaters with low heat outputs and for the heating of accessories.

4.212 *Hot-cold Air Metering Control* consists of one or more thermostats which operate a proportioning device. This device, in turn, adjusts a set of dampers or similarly regulates air flow in such a manner as to permit more or less cold air to mix with the heated air. In order to keep the air flow along the heat exchanger constant, the unused portion of the hot air is spilled overboard. The output of the heater is usually unchanged so that the total heat expended remains the same although the air temperature is increased or decreased, as the case may be.

In large cabins, several thermostats are arranged in parallel and so distributed as to maintain a constant, average temperature throughout the cabin. It is not unusual to place at least one thermostat in the foul-air spill since the temperature of the used air is indicative of the cabin temperature. The desired temperature range is adjusted by means of a regulator, located in the flight deck or inside the cabin and near a thermometer, as shown in Fig. 61, which illustrates the automatic heat control aboard an Eastern Airlines transport.

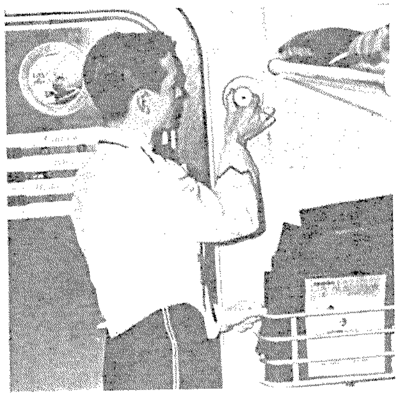

Fig. 61

The metering devices for positioning of the mixing dampers may be based on one of a number of principles. In the Cunningham Control of the General Controls Company the increase or decrease of the cabin temperature will expand or contract, respectively, a gas inside a bulb. This pressure change is transmitted to a bellows which serves to regulate the hydraulic pressure in the operating mechanism. This control is shown in Fig. 62. The Barber-Colman control uses a proportioning motor which is shown in Fig. 63. The control manufactured by Minneapolis-Honeywell employs an electronic principle.

Controls of this type are usually found in connection with exhaust air heaters in which the mass flow of ventilating air over the heat exchanger should remain constant to prevent overheating. However, they are also used in other heating systems of the central-heater variety.

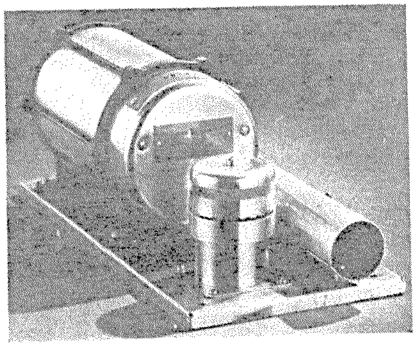

Fig. 62

4.213 *Fuel-metering Control*—In this method the output of the heater itself is modulated. The automatic metering device may be similar to one of those described under 4.212 and regulate the fuel flow either by means of a needle valve or, in heaters employing integral fuel pumps, by changing the speed of the pump.

Simultaneous control of the ventilating air flow is necessary, if it is required to maintain constant outlet temperatures. This can be accomplished either by tandem operation or by a separate control, such as a thermostatically operated shutter in the ventilating air outlet.

In internal-combustion heaters, regulation of the combustion air with change in fuel flow is normally coupled with the high-altitude control for constant mass flow.

Fuel-metering control is mostly used in internal-combustion heaters but is also quite common in exhaust steam or liquid heaters in which, instead of the fuel, the flow of steam or the hot liquid is regulated.

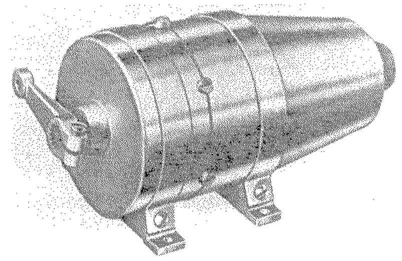

Fig. 63

4.22 *Altitude Control*—While the controls discussed above apply to most types of aircraft heaters, the following are exclusive for internal-combustion heaters. Very important in this respect is the previously discussed High-Altitude Control which maintains constant mass flow of the combustion air at all altitudes (see 3.5). Installation of such a control in an Altiheater is shown in Fig. 60 (2).

Regulation for constant mass flow of the ventilating air must be incorporated if its lack would result in objectionable overheating of the air at altitude. This is best illustrated in the following example in which a 50 stu capacity heater is needed for anti-frosting of a transparent enclosure. If the air flow is adjusted for a sea level D.O.A.T. of −35° and a warm air temperature of 165°, then, according to equation (3):

$$50{,}000 = 60 \times 0.24 \times q \times 0.075 \times 200$$

and:

$$q_s = 232 \text{ cfm}$$

If the air volume would remain unchanged up to an altitude of 35,000 feet, the temperature differential at that altitude would be:

$$\Delta t_a = \Delta t_s \times 0.075/0.025 = 600°$$

Even with an outside temperature of −100°, the temperature of the heated air would still be 500° which, of course, is far too high for the indicated purpose.

If the air flow at sea level is calculated for lower than rated heat output and the output increased at high altitude—either manually or automatically—the change in the temperature differential would be even more drastic. Since decrease of heat output at higher altitudes would defeat the purpose of the heater, there remains only a proportionate increase in air volume to prevent overheating of and damage to the transparent enclosure. (See 4.213.)

4.23 *Fuel Pressure Control* is always desirable and particularly needed in heaters which do not use forced fuel such as supplied by a pump. The lack of this control will aggravate regulation of the proper fuel-air ratio and efficient combustion. A control of this type is shown again in Fig. 60 (3).

4.24 *Ignition Control* is operated by a thermostat within the heater which turns the ignition off as soon as combustion takes place.

4.3 CONTROLS, AUTOMATIC, SAFETY. The purpose of the automatic safety controls is to make the heater inoperative, if its operation is affected in any way. In this case, fuel and air supply as well as ignition should be shut off immediately, and starting of the heater be made impossible unless the cause for shut-down has been remedied.

4.31 *Ram Control* is operated by the static pressure of the ventilating and combustion air and shuts the heater off, if one or both of these supplies are insufficient for safe operation. In heaters which are provided with blowers for ground operation and scoops for flight, the ram control may be used to turn the blower on automatically, if the heater is operated on the ground or the ram falls below a set minimum. In Fig. 60 (6) shows a model of such a control.

4.32 *Ignition Safety Control*—As previously mentioned, a relay inserted in series with a hot wire igniter will turn the heater off, if ignition fails. A control of this kind is denoted by (5) in Fig. 60.

4.33 *Fuel Control*—The purpose of this control is to shut off ignition and air supply, if there is insufficient or no supply of fuel, so as to prevent explosions due to irregular fuel flow, excessive leading and carbonization of the combustion circuit, useless current drain and introduction of unheated air.

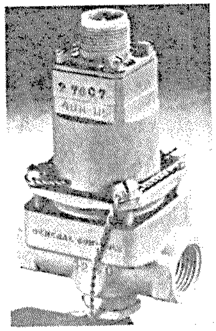

Fig. 64

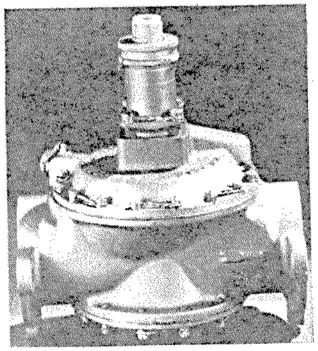

Fig. 65

4.34 *Shut-Off Valve*—Insertion of an automatic shut-off valve into the fuel supply line is mandatory in order to stop the fuel flow immediately in case of failure. This valve is usually operated by one of the other safety controls, such as the ram or ignition control. Figure 64 shows a General Controls shut-off valve for liquid or gaseous fuels which is solenoid operated. A similar model, but for fuel-air mixtures supplied by the engine, is shown in Fig. 65.

4.35 *Overheat Control* consists essentially of a thermostat which either operates a shutter to permit larger flow of ventilating air with increasing temperature, or turns the heater off, if the maximum pre-adjusted temperature is exceeded.

4.36 *CO Control,* discussed before, operates a relay in case the percentage of carbon monoxide in the ventilating air or in the cabin reaches the permissible limit, usually one part in 20,000. The relay, in turn, shuts the heater off and may also be used to open the fresh air intake fully. Occasionally, it is specified that a warning signal be set off by the relay, too.

It is not absolutely essential that all of the controls enumerated above are incorporated in a heater to make it foolproof. In some cases, one or another control can be omitted or combined with others. Furthermore, every added control is a potential source of failure. Therefore, in specifying or designing an internal-combustion heater, it must be attempted to obtain the maximum degree of safety and dependability with a minimum of both manual and automatic control devices.

5.0 SPECIFICATIONS

One of the greatest difficulties in producing heaters to given specifications is the fact that, quite often, these specifications are either incomplete or unreasonable. It must be realized that, in specifying one factor, another may be automatically established, and that failure to check all factors against each other may make it impossible for the designer to comply fully with the expectations of the procuring agency.

If, for instance, the temperature rise across the heater and its capacity are specified, it would be superfluous to specify also a desired mass flow for the ventilating air since it is calculated from the former data. The following information, however, should always be included in specifications for internal combustion heaters:

5.1 RATED CAPACITY. Only the required maximum output should be specified and not be augmented by a value for the permissible drop in capacity with increasing altitude since a well designed heater must maintain constant output up to the service ceiling.

5.2 SERVICE CEILING. This figure may not necessarily coincide with the service ceiling of the airplane and should represent the highest altitude at which heat may be required.

5.3 MAXIMUM CURRENT CONSUMPTION. Current consumption does not decrease in proportion with decreasing heater capacity since most controls, igniters etc., draw a definite amount of current which is little affected by the size of the heater and its output. A current drain of 5 amp at 24 volts of continuous load and 10 amp of intermittent load are reasonable figures for heaters exceeding 20 stu capacity. Somewhat higher values should be granted for heaters over 200 stu capacity as their controls may be more complex, and larger air flows require more power for regulation beyond certain limits.

The current drain of the blowers should not be included since, for a given heat output and mass flow of air, this value is definitely established.

5.4 MEANS OF COMBUSTION AIR SUPPLY. As shown before, it is necessary to specify whether combustion and ventilating air supply should be combined or separate. The next choice is that of a suitable combination of scoop and/or blower from the list given under 3.2. The methods for calculation discussed in previous chapters provide an indication of required scoop or blower sizes under various conditions which should be the basis for selection of the most appropriate method.

5.5 MEANS OF VENTILATING AIR SUPPLY. The same considerations apply as outlined under 5.4. Due to the large air quantities involved, ground and flight requirements must be clearly defined.

5.6 SPEED OF THE AIRPLANE. Minimum, medium and maximum cruising speeds must be known in order to determine the ram pressures available for scoop operation.

5.7 MEANS OF FUEL SUPPLY. It must be stated whether gravity feed or forced feed is desired. If the former is specified, the available pressure head at the proposed location of the heater must be given.

5.8 CONTROL. It is necessary to outline which of the following means and methods of control are desired: (a) remote or heater-panel control; (b) manual or automatic; (c) on-off or modulating.

Modulating control for internal-combustion heaters should never be required to go below 20% of rated capacity.

5.9 HOUSING. Whenever possible, regular production units should be selected in which the components are arranged in the best possible manner, as developed through numerous tests. However, if special conditions exist which require odd shapes of the heater housing, enough space must be allotted to permit a suitable installation. This space should not be determined by the cubical content of a production heater housing as many parts cannot be condensed in their relationship to each other.

5.10 POWER SUPPLY. If it is desired to obtain an integral gasoline engine with the heater to supply the motive and electric power for its operation, no further specifications are necessary in addition to the statement that such an engine is wanted.

5.11 MISCELLANEOUS. Miscellaneous specifications should refer to such features as are not commonly found in conventional heaters and are necessitated by unusual conditions or applications.

The minimum outside, ambient temperature (D.O.A.T.) should be considered established by the service ceiling. Weight, efficiency and permissible back pressures for both combustion and ventilating air supply are likewise based on standardized values which have been discussed before.

Details of design, such as the method of heat transfer, prevention of leading, ignition and similar items must be left to the individual manufacturer who will attempt to better the accepted values for weight, efficiency and current consumption as much as possible without impairing the safe and efficient operation of his product.

6.0. TESTING

Apart from the conventional tests specified for aircraft accessories, the following test program should be applied to internal combustion heaters:

6.1 PERFORMANCE TEST. This test must yield complete data on fuel consumption, electric current drain, air volumes, back pressures and efficiency at various heat outputs from minimum to maximum.

Incidentally, there are two simplified methods of measuring heat outputs in the course of such tests. The first one consists of measuring the fuel drawn from a graduate during operation and calibrating heat output versus the seconds required for consumption of one ounce of gasoline. This method can be employed only if the overall efficiency of the heater is known to be stable.

In the other method, equation (3) is assumed as:

$$H = 60 \times 0.24 \times 0.075 \times q \times \Delta t = 1.08 \times q \times \Delta t$$

Thus, the heat output at sea level equals just about the ventilating air quantity times the temperature differential across the heater. Since, in tests of this kind, the air quantity and inlet temperature are relatively constant the performance of the heater can be continuously checked, with fairly good accuracy, on a curve showing heat output as a direct function of the outlet temperature.

6.2 ALTITUDE TEST. This test must prove that the heater will operate from sea level to its service ceiling, with heat output and air temperatures remaining constant for fixed settings.

6.3 COLD TEST. The heater should be exposed to a temperature of −100° until all of its components have reached that temperature. Then the temperature should be increased to −60°, and the heater must here start and operate without effort.

6.4 STARTING TEST. The heater must start immediately and without explosions under the following conditions:

a. In all positions;
b. At all settings of the modulating control;
c. At all altitudes from sea level to service ceiling;
d. Within any time after shut-down (hot-starting test);
e. At any temperature above −60° (cold-starting test).

Proper combustion must take place within one minute after start, and full rated heat output must be delivered within three minutes after start.

6.5 LIFE TEST. In order to test the heater under conditions of maximum heat and mechanical stresses, it should be mounted on a vibrating support and operated in the following manner: Three hours at maximum output, one hour of cooling off, three hours of maximum output, one hour of cooling off, etc. until one hundred hours of actual operation are reached. The heater may then be taken apart and serviced. This procedure is repeated two more times for military heaters, and nine more times for commercial units so that the test period of actual operation is 300 hours for the former and 1000 hours for the latter, with service periods allowed after every hundred hours.

Higher requirements are not only unnecessary in view of the fact that the life of the airplane itself is rather limited, but would also result in far heavier and less efficient designs.

7.0 REPRESENTATIVE DESIGNS

The flexibility of internal-combustion heaters is very well illustrated by the complete line of models manufactured by the Stewart-Warner Corporation. As mentioned before, this company has pioneered the use of internal combustion for aircraft heating and its products are, therefore, representative of the work done in this field.

The units shown in the following photographs are some of the Stewart-Warner models which are now in use on planes of all makes and types.

Figure 66 shows an 80 stu duct heater which receives its combustible mixture from connections across the aircraft engine supercharger. Ventilating air is usually supplied by a ram, although a blower may be substituted if desired.

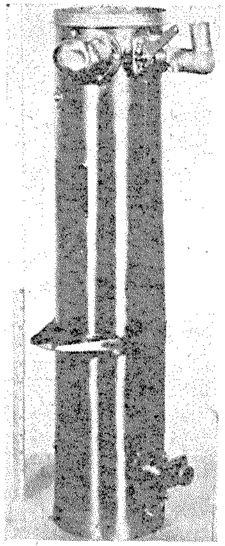

Fig. 66

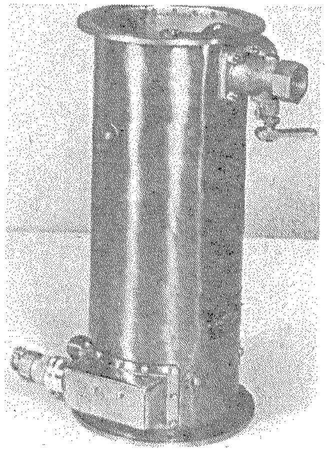

Fig. 67

The heater illustrated in Fig. 67 is similar to the previous model, with the exception that it is rated at 40 stu capacity instead of 80. Both models lend themselves, among others, very well for such duct applications as required for anti-frosting.

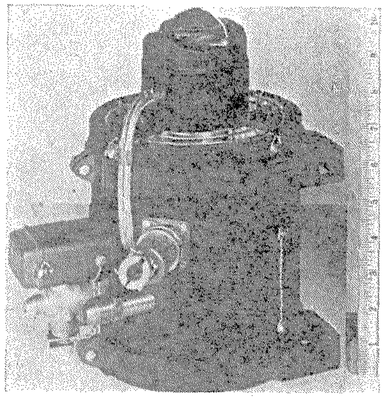

Fig. 68

Figure 68 illustrates a 10 stu engine-connected heater. Ventilating air is supplied by a small, motor-driven fan. Its weight is only 10¾ lb. It is essentially a local spot

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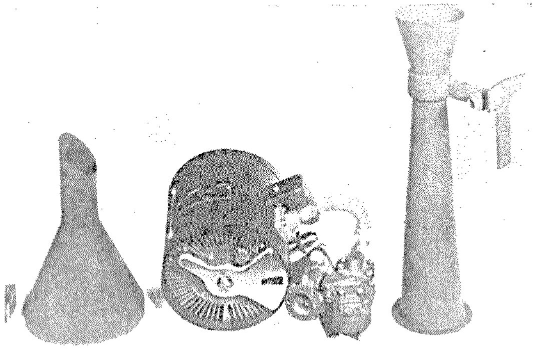

Fig. 69

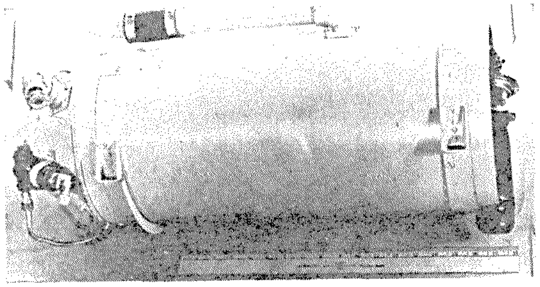

Fig. 70

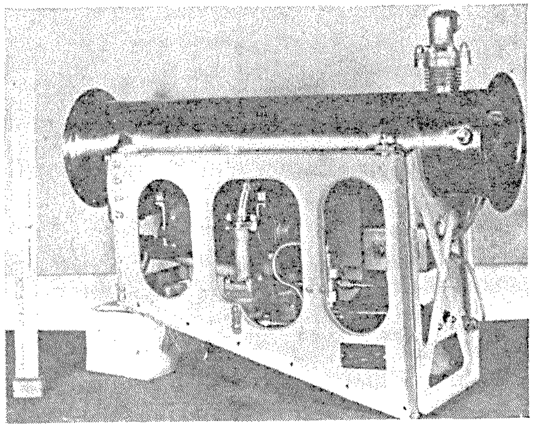

Fig. 71

heater which may be used not only for the heating of personnel but also of guns and other equipment.

The heater shown in Fig. 69 is an adaptation of the previous model to unsupercharged airplanes, particularly light planes. In this adaptation the heater receives ventilating air from a ram while combustible mixture is supplied by a separate carburetor. Flow through the carburetor and heater is brought about by a venturi located in the air stream. The weight of this model is only 8½ lb.

The heater in Fig. 70 has a capacity of 100 stu and is normally ram operated. It has its own carburetor and diverts a portion of the ram air for carburetion and combustion. This exceedingly compact unit weighs only 29 lb. A heater of this type is very suitable for empennage anti-icing.

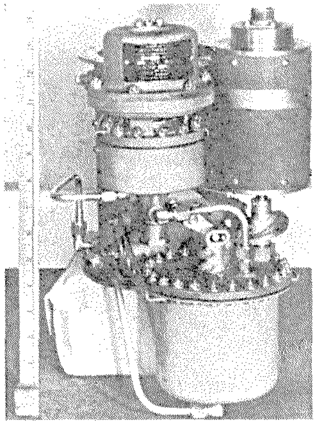

Fig. 72

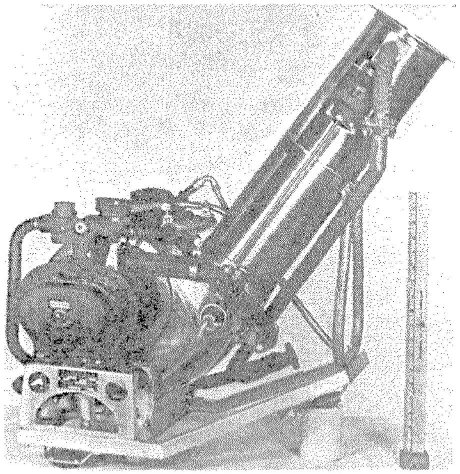

Fig. 73

The heater shown in Fig. 71 and the control valve in Fig. 72 are normally used together. The heater has an output of 80 stu and is intended primarily for use with cabin supercharged airplanes. Air from the supercharger passes through the heater and thence to the cabin, a portion of this air being diverted for combustion. A proper pressure differential across the combustion side of the heater is automatically maintained at all times and under all operating conditions by the automatic regulating valve.

Figure 73 shows an 80 stu heater which needs only a gasoline connection to operate. A small gasoline engine drives a centrifugal blower for supplying ventilating air and a supercharger which supplies a combustible mixture to the heater and the engine. The heater is thermostatically controlled to maintain a constant temperature output. Its weight is 102 lb complete.

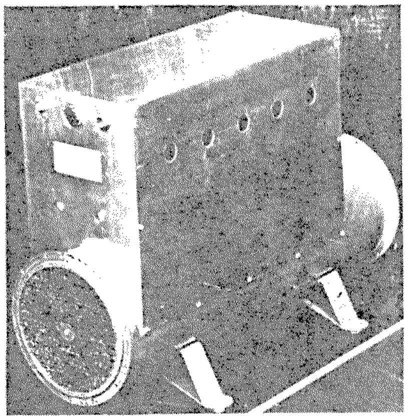
Fig. 74

Aircraft heaters of the internal combustion type are also produced by a number of other manufacturers such as the Selas Company, Surface-Combustion and Solar. The Solar Altiheater shown in Fig. 74 is designed, primarily, for operation at high heat output and altitude. At a weight of only 23 lb complete, which includes an integral fuel pump, it delivers 250 stu up to 40,000 ft. During ground tests, capacities as high as 400 stu were obtained with the same model. This heater is very well suited for applications requiring high capacities in remote sections of the plane, such as empennage anti-icing.

8.0 Miscellaneous Designs

The method of internal combustion is used in a few other heating systems whose principles differ somewhat from those described above.

8.1 INTERNAL-COMBUSTION STEAM HEATER shown in Fig. 75 generates steam by placing a water-carrying copper coil inside of the combustion chamber. Thus, the heater is a combination of an internal combustion and a steam heater, with most of the disadvantages of both and but few of their advantages. It has not proven very practical for use on aircraft due to its size and weight. In addition, it requires a combination of combustion and steam controls which make its operation quite difficult and not very dependable. The unit shown had 2 boilers and was rated at 80 stu.

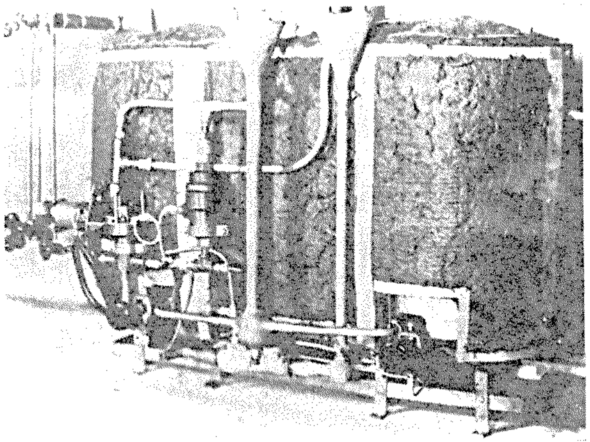
Fig. 75

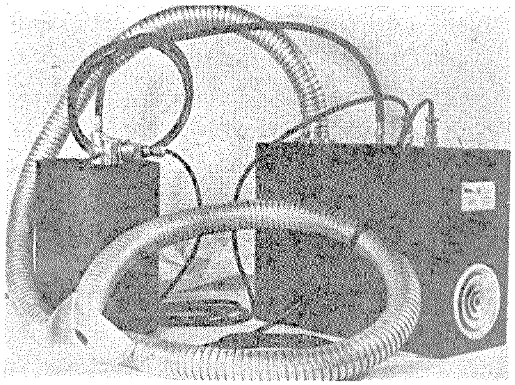
Fig. 76

8.2 PROPANE-FIRED ALTIHEATER. Another deviation from the conventional internal-combustion principles is the propane-fired Altiheater shown in Fig. 76. As its name implies, it is not fueled by gasoline but by propane, a liquefied petroleum gas. The main advantages of using propane are that its combustion products are not toxic and can even be mixed with the ventilating air. This results in practically 100% efficiency and the elimination of heat exchangers, which in turn brings about a sharp reduction of back pressures both in the ventilating and combustion air circuits. Therefore, a small scoop such as the

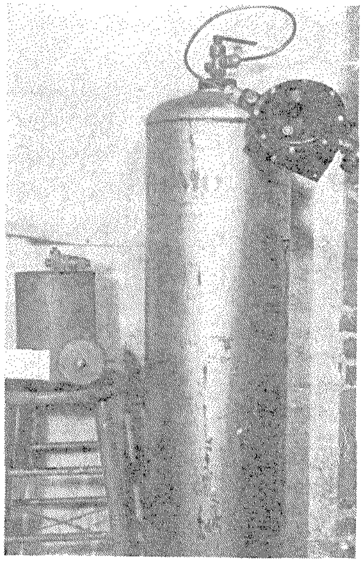
Fig. 77

one shown in Fig. 76 is sufficient to supply all air needs under most conditions. In addition to the greater efficiency, the heat content of propane is about 10% higher than that of gasoline so that a considerable saving in the weight of fuel consumption can be obtained. Apart from that, the lack of heat exchangers permits a lighter and more compact unit for comparative heat outputs.

The fuel is carried in a separate tank, also shown in Fig. 76. This particular tank has a capacity of almost 100,000 btu, at an empty weight of less than two pounds. It is made from 17ST aluminum and provided with a solenoid shut-off valve. Figure 77 shows this tank with its fuel pressure regulator, in comparison with a conventional propane tank and regulator as used for household and industrial purposes. An interior view of the heater had been shown in Fig. 60.

The only major disadvantage of this heater is the problem of refueling. While, during peacetime, propane either is or easily can be made available at all landing fields, this supply problem is so serious during times of war, that the manufacture of this heater has been discontinued for the duration: It has been replaced by gasoline-fired units such as the one shown in Fig. 74.

XVI

THEORY OF EXHAUST-GAS HEAT EXCHANGERS

The apparent complexity of the principles underlying heat transfer has deterred many engineers from closer study of this science until they were compelled to use it. However, once the fundamentals are understood, it becomes evident that the theory of heat transfer is not only quite elementary but covers a wider field than is commonly realized.

This is particularly evident in the design of aircraft and its components. Proper heat transfer is needed for the engine as well as the supercharger, the anti-icing scheme and the numerous tasks of cabin and accessory heating. Another application of increasing prominence is the utilization of the heat in the engine exhaust gases for heating purposes. For this reason a text on aircraft comfortization would not be complete without an analysis of exhaust-gas heat exchangers.

The possibilities of this method of heat supply were pointed out in Chapter XIII, and there is no doubt that the large heat quantities which can thus be recovered without expending fuel or electric current can solve many of the pressing problems of anti-icing, antifrosting and the other requirements of heat supply on modern airplanes.

It would go far beyond the scope of this book to attempt to cover the field of heat transfer or to even discuss aircraft heat exchangers to any extent. In addition, design details of these accessories are restricted for obvious reasons. However, it is essential to be sufficiently familiar with the theory of heat exchangers to understand their operation and mutual relationship with other components of the airplane and also in order to select them properly.

1.0 Fundamentals of Heat Transfer

If two bodies, either fluid or solid, which are of different temperature, are brought in contact with each other, heat will flow from the warmer body to the cooler one until the temperatures of both are the same. This is analogous to two vessels which are filled with water at different levels. If these vessels are connected, an exchange takes place and water flows from the vessel with the higher level to the one with the lower level until the height of the water column in both vessels is the same.

In heat transfer, the warmer and cooler fluid are usually separated by a solid layer which is called the *heat transfer surface*. If heat exchange is not desired, this layer is made of materials which offer high resistance to heat flow and is so designed as to have as small a common or heat transfer surface as possible. However, if the purpose of this arrangement is to transfer the heat contained in one fluid to the other, the heat transfer surface is large and thin, and made from a good heat conductor, such as metal.

If both fluids are enclosed in a very well heat-insulated container and separated by a metallic wall, the warm fluid will heat the wall which, in turn, heats the cool fluid. After a certain length of time, both fluids as well as the wall will have assumed the same temperature which lies somewhere between the original temperatures of the two fluids. The system is now said to be in *thermal equilibrium*. The length of time required for completion of the heat exchange depends on numerous factors, such as the conductivity of the wall, the specific heat of the fluids, their mass and others.

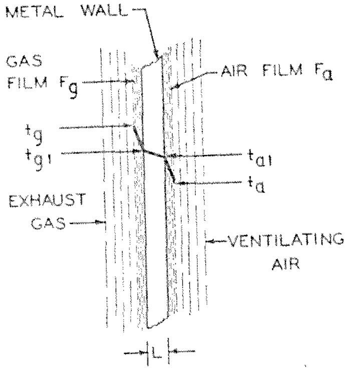

Fig. 78

If it is necessary to transfer large heat quantities in a short time, both fluids must be in motion, and the faster this motion, the more rapid the heat transfer. In other words, the heat transfer increases with the mass flow of the fluids on both sides.

Referring now to Fig. 78, a wall of the thickness L separates a hot fluid—for instance, exhaust gas—from a cold fluid, such as ventilating air scooped in during flight. The temperature of the exhaust gas is t_g and that of the cold air t_a. Both the air and the gas are assumed to be in rapid motion.

As heat is transmitted from the gas to the air, a certain amount of resistance to the heat flow is offered not only by the wall itself but also by films F_a and F_g on either side which are of indefinite thickness. The resistances of the latter are usually considerably larger than that of the former. Thus, the temperature t_g drops to t_{g_1} at the surface of the plate, then to t_{a_2} at the air side of the plate and to t_a beyond the air film F_a.

If H is the rate of heat flow in btu/hr, and A the area of the plate, then the heat flow through the gas film is:

$$H = f_g \times A \times (t_g - t_{g_1})$$

and for the plate:

$$H = k/L \times A \times (t_{g_1} - t_{a_1})$$

and for the air film:

$$H = f_a \times A \times (t_{a_1} - t_a)$$

in which f_g and f_a are the so-called film coefficients of the gas and air, respectively, k the thermal conductivity of the wall and the factor k/L its thermal conductance. f_g, f_a, and k/L are measured in btu/hr/°F/unit area.

The reciprocals of these values, $1/f_1$, $1/f_2$, and L/k, are the resistances of the two films and the plate. It should be noted that the conductance of the plate contains the element of thickness while the factors for the films do not.

The total resistance to the flow of heat, per unit area, equals the sum of the individual resistances so that:

$$R = 1/f_g + L/k + 1/f_a$$

The overall conductance of the plate and films is called U and is the reciprocal of R so that:

$$U = 1/R$$

Accordingly, the heat transferred from the gas to the air is expressed by the following equation:

$$H = U \times A \times (t_g - t_a) \qquad (1)$$

This equation is the fundamental formula in the calculation of heat transmission and has been briefly discussed before in connection with anti-icing and anti-frosting. Its application to exhaust-gas heat exchangers is somewhat involved and best explained by carrying out a sample calculation.

2.0 Sample Calculation of Heat Exchanger

Since, in many cases, available data are quite meager and incomplete, it is advisable to base all calculations on as few given values as possible. Therefore, only the following data shall be assumed as known:

Rated Horsepower of Engine:	1000
Number of Exhausts:	Two
Fuel-Air Ratio:	0.07 (1:14.3)
Cruising Altitude:	15,000 ft
True Air Speed at Sea Level:	200 m/hr.

The purpose of the calculation is to find the design data for an exhaust air heater of 250,000 btu/hr capacity and a temperature increase across the heater of 300° at maximum output, so that proper specifications can be written and all factors pertaining to the installation on the plane are established.

It is, consequently, desired to compute the following values:

2.1. Overall Efficiency of Heat Transfer Required to Obtain 250 stu;
2.2. Exhaust Gas
  2.21 Quantity;
  2.22 Back Pressure;
  2.23 Temperatures;
2.3. Ventilating Air:
  2.31 Quantity;
  2.32 Back Pressure;
  2.33 Air Intake;
2.4. Size of Heat Exchanger

The likewise desirable data for weight, efficiency at altitude and methods of design will be discussed in subsequent sections.

The calculations shall be made for the following conditions:

Rated heat output to be measured at sea level;
Mass flow of air and gas to be constant;
Aircraft flying at cruising speed;
Engine operating at 60% of rated power;
D.O.A.T. (Design outside, ambient temperature) = −60°F

2.1 EFFICIENCY OF HEAT TRANSFER REQUIRED TO OBTAIN 250 STU. As the engine is assumed to be operating at 60% of rated power, it delivers 600 hp which, according to the curve in Fig. 52, provides a total of about 2,000,000 btu's of heat in the exhaust. As there are two tail pipes, about half of this amount or 1,000,000 btu will be available in each. If the heat exchanger is to deliver a maximum of 250,000 btu/hr, it must extract about 25% from the theoretical maximum which is considered a reasonable percentage. (These considerations apply only to air-cooled engines.)

The calculation of the actual efficiency requires knowledge of the gas inlet and outlet temperatures and will, therefore, be made after these values have been computed.

2.2 EXHAUST GAS. In calculating the quantity and temperatures of the exhaust gas, it shall be assumed that no energy is lost between the engine ports and the heat exchanger, for instance, by insertion of a turbo supercharger. This, however, shall not apply to the drop in temperature due to radiation and convection.

2.21 *Quantity*—The hourly mass flow of the exhaust gas can be derived from the following equation:

$$W_g = \text{Horsepower delivered} \times 60 \times 0.12 \text{ lb/hr} \qquad (2)$$

in which the value 0.12 is a conversion factor. As it was assumed that the engine was operated at 60% of its rated power,

$$W_g = 600 \times 60 \times 0.12 = 4320 \text{ lb/hr}$$

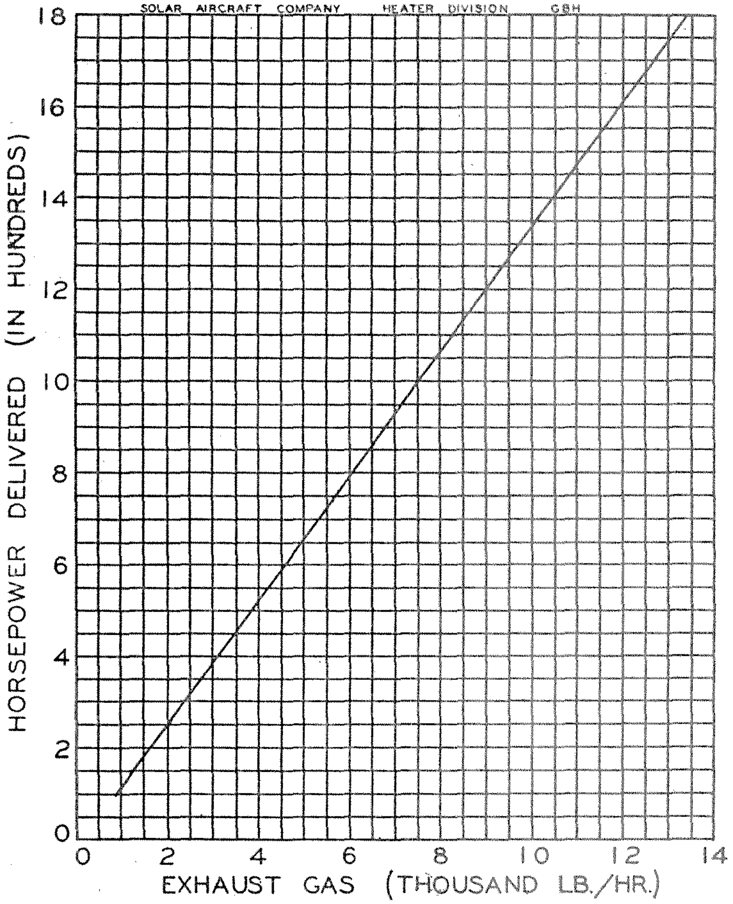

Fig. 79

Accordingly, about half that much or 2160 lb/hr of exhaust gas flow through each of the two tail pipes. These values can be read directly from the curve in Fig. 79.

The corresponding volume depends, with all other factors remaining constant, on the temperature of the gas and the altitude. As can be seen from the curve in Fig. 80, the temperature of the exhaust gas at 60% of rated power is about 1740. This curve gives very good approximations for engines above 800 hp.

Figure 81 provides the density for the exhaust gas at various altitudes and temperatures. Accordingly, 2160 lb of gas at 1740° would equal, at sea level:

$$Q_s = 2160/(0.018 \times 60) = 2000 \text{ cfm}$$

and, at 15,000 feet:

$$Q_a = 2160/(0.01 \times 60) = 3600 \text{ cfm}$$

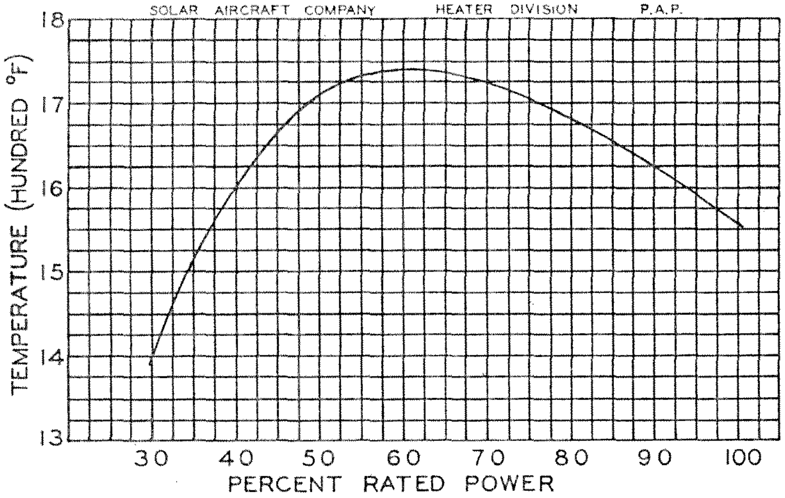

Fig. 80

Another factor in connection with the quantity of exhaust gas which is important in the design of the heat exchanger, is the diameter of the tail pipe. This value is usually furnished by the engine manufacturer. However, a useable approximation can be obtained by calculating the pipe area for 0.035 sq in./hp. The area must, of course, be figured for the maximum horsepower which, in this case, would be about 1200. Therefore,

$$A_g = 1200 \times 0.035 = 42 \text{ sq in.}$$

Consequently, the diameter of the tailpipe is

$$d_g = 7.31''$$

Actually, the diameter should be somewhat larger and a value of 8″ is normal for engines of this rating. If there are two tailpipes per engine, the minimum area per tailpipe would be 21 sq in. and the diameter of the pipe leading to the heat exchanger $d_g = 5.17''$. A value of 5.25″ O.D. will be used in the following.

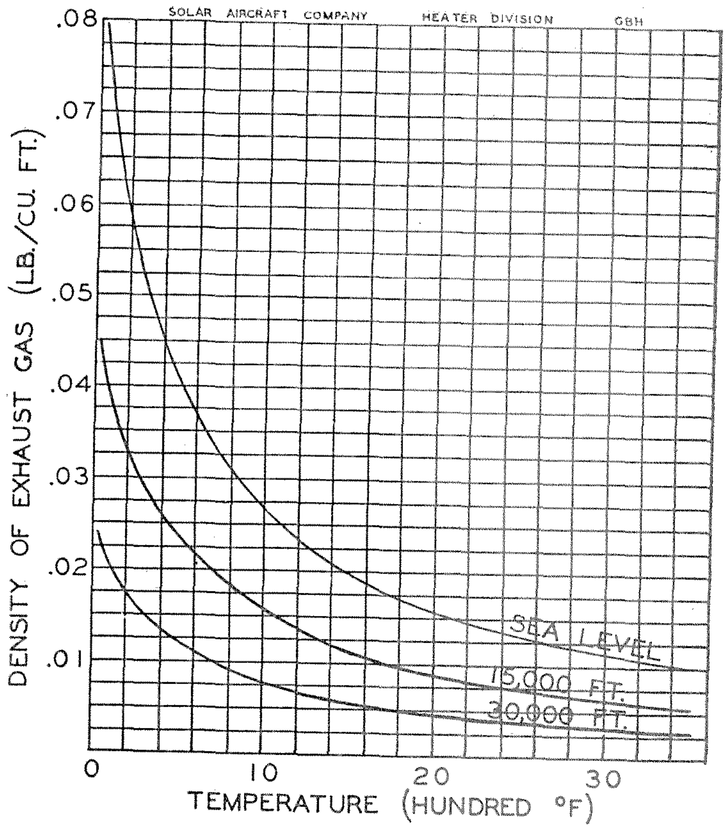

Fig. 81

2.22 *Back Pressure*—The resistance to the flow of the exhaust gas through the heat exchanger depends largely on the design of the latter. As will be shown later, the efficiency of the heat transfer is increased by increasing the perimeter with respect to the flow area which, in turn, results in larger pressure drops. Since the maximum permissible back pressure at sea level is usually specified by the procuring agency, it is necessary to arrive at a compromise which will yield the desired performance without exceeding the specified resistance.

As a rule, presently used heat exchangers will be found to have pressure drops of about 1.5″ H_2O per 100 stu at sea level.

Once the design of the heat exchanger has been established, back pressures at both sea level and altitude can be computed by means of the previously described calculations (see Chapter IX).

2.23 *Temperatures*—In order to arrive at conclusive values for the heat transfer, it is necessary to establish the gas temperatures at the inlet and outlet of the heat exchanger as well as the average temperature within the heater.

Figure 80 has shown that the gas temperature at the port of the engine is 1740°, at 60% of rated power. Assuming that the length of the exhaust pipe from the engine port to the heat exchanger inlet is 3 ft, it is obvious that a certain amount of heat is lost by radiation and convection, and that the temperature of the gas drops correspondingly. This drop can be generally calculated on the basis that the heat loss for bare pipes will amount to about 7 btu/sq ft/hr/°F. Then:

$$\Delta t_p = \frac{7 \times \Delta t_z \times A_p}{c_g \times W_g} \qquad (3)$$

in which: Δt_z = average temperature differential between the gas and the surrounding air; A_p = the area of the exhaust pipe from the port to the heater inlet, in sq ft; c_g = the specific heat of the gas; and W_g its mass flow in lb/hr.

Δt_z is calculated from the average temperature of the gas within the pipe which shall be assumed as 1720° and the temperature of the surrounding air which is about 150°. Then:

$$\Delta t_z = \frac{1720 - 150}{2} = 785°$$

Since the diameter of the exhaust pipe is 5.25″ and its length 3 ft, the radiating area is

$$A_p = \frac{5.25 \times \pi \times 3}{12} = 4.125 \text{ sq ft}$$

The specific heat of the exhaust gas at various temperatures can be read from Fig. 82. At 1720°, c_g = 0.316. The weight flow was W_g = 2160 lb/hr. Thus, equation (3) becomes:

$$\Delta t_p = \frac{7 \times 785 \times 4.125}{0.316 \times 2160} = 33°$$

Therefore, the temperature of the gas at the exchanger inlet is:

$$t_{gi} = 1740 - 33 = 1707°$$

The outlet temperature is computed by solving the formula which was used in calculating heat losses, for the temperature differential so that:

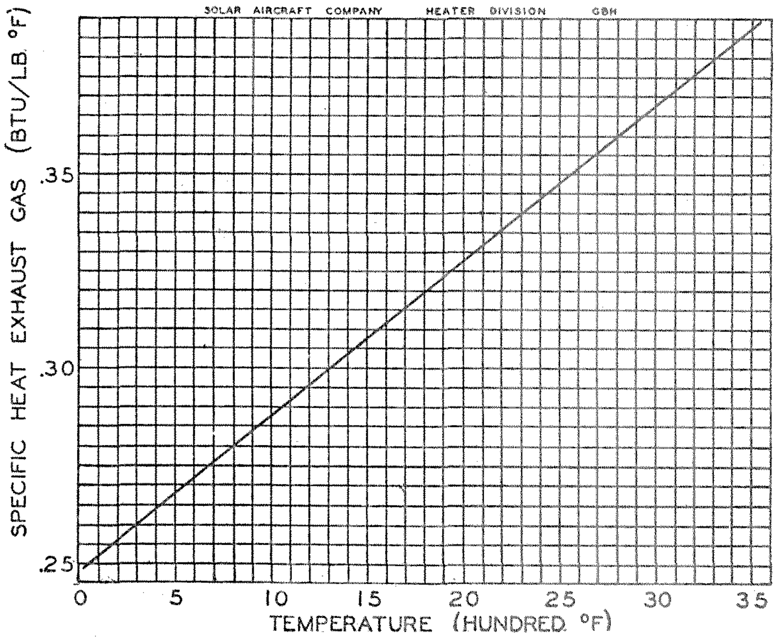

Fig. 82

$$\Delta t_g = \frac{H}{W_g \times c_g} \qquad (4)$$

The heat amount extracted from the exhaust gas while passing through the heat exchanger is 250,000 btu/hr. Inserting this value and those for the mass flow and specific heat, equation (4) yields:

$$\Delta t_g = \frac{250{,}000}{2160 \times 0.316} = 366°$$

Therefore, the outlet temperature of the gas is:

$$t_{go} = 1707 - 366 = 1341°$$

And the average temperature of the gas within the exchanger is:

$$t_{gm} = 1707 - 366/2 = 1524°$$

It is now possible to calculate the actual efficiency of the unit, which is the ratio of the heat extracted from the exhaust to the heat available. The heat extracted by the air is:

$$H = c_g \times W_g \times (t_{gi} - t_{go})$$

and the total heat available is:

$$H_g = c_g \times W_g \times (t_{gi} - t_{ai})$$

in which the subscripts g and a refer to gas and air, respectively, and the subscripts i and o to inlet and outlet, respectively. The amount of H_g depends on the temperature differential between the gas and air inlet temperatures which account for the values t_{gi} and t_{ai}. Therefore, the efficiency of the heat exchanger is:

$$E = \frac{t_{gi} - t_{go}}{t_{gi} - t_{ai}} \tag{5}$$

The D.O.A.T. for the ventilating air was specified as $-60°$ so that:

$$t_{ai} = -60°$$

Inserting the values for the temperatures into equation (5),

$$E = \frac{1707 - 1341}{1707 + 60} = 0.21 \text{ or } 21\%$$

This checks quite well with the previously found value of 25% and shows that the use of the curve in Fig. 52 for determining the heat available in the exhaust yields a sufficiently close approximation for most purposes. It must be remembered also that the latter method is independent of the minimum design temperature for the ventilating air which, of course, is an arbitrary value.

2.3 VENTILATING AIR. It shall be assumed that the ventilating air is furnished by a ram and that there is no heating of the air prior to its entry into the heat exchanger.

2.31 *Quantity*—The required mass flow of the ventilating air is obtained by means of equation (4) so that:

$$W_a = \frac{H}{c_a(t_{ao} - t_{ai})}$$

in which W_a is the weight flow of the air in lb/hr, H the heat imparted to the air in btu/hr, c_a the specific heat of the air, and t_{ai} and t_{ao} the air temperatures before and after passing through the exchanger, respectively. Therefore

$$W = \frac{250{,}000}{0.24 \times 300} = 3480 \text{ lb/hr}$$

At sea level, this corresponds to:

$$q_a = 3480/(60 \times 0.075) = 773 \text{ cfm}$$

and at 15,000 feet, at which the average air density is 0.0475 lb/ cu ft:

$$q_a = 3480/(60 \times 0.0475) = 1220 \text{ cfm}$$

2.32 *Back Pressure*—The pressure loss of the ventilating air while passing through the heat exchanger depends again, to a large extent, on the design of the heater. As pointed out, in Chapter XIII, experience has shown that, as a rule, a pressure drop of 1″ H_2O per 1000 lb of air at sea level is a reasonable figure to specify. Accordingly, a pressure drop of about 3.5″ can be expected for this particular example.

It will be remembered that this value increases for constant mass flow at altitude as the ratio of the volumes or inverted ratio of the densities. Consequently, the pressure drop at 15,000 ft will increase to

$$\Delta P_a = 3.5 \times 1.58 = 5.52'' \ H_2O$$

2.33 *Air Intake*—As shown before, the ram pressure of the air is found by the following formula:

$$V = 1096.5 \sqrt{h/d} \tag{6}$$

in which:

V = True Speed of the Plane, in ft/min
h = Ram Pressure, in inches H_2O

d = Density of Air, in lb/cu ft
Solving this equation for the ram,

$$h = \left(\frac{V}{1096.5}\right)^2 \times d = \left(\frac{200 \times 5280}{60 \times 1096.5}\right)^2 \times 0.075 = 19.4'' \text{ H}_2\text{O}$$

This is the theoretical force which would be exerted during flight against a flat plate of unit area. (In order to obtain the actual force, this value would have to be multiplied by 0.8.) In utilizing the ram to drive a desired amount of air through the system, the static resistance to the flow of air at that rate must be deducted from the available ram. The difference is then the pressure which determines the velocity of the air.

The resistance in the system is composed of the pressure loss in the heat exchanger, which was assumed to be 3.5″, and the losses in the rest of the air circuit, such as ducts, dampers and the like. It shall be assumed that these losses have been calculated to be 5″, so that the total loss for the given mass flow of air at sea level is 8.5″ H_2O. Deducting this from the computed ram, the actual pressure head is:

$$h_s = 19.4 - 8.5 = 10.9'' \text{ H}_2\text{O}$$

This value is now inserted into equation (6) in order to obtain the velocity of the air and:

$$V_s = 1096.5\sqrt{10.9/0.075} = 13{,}200 \text{ ft/min}$$

The necessary inlet area is then found by the relation:

$$A = Q/V \tag{7}$$

in which

A = Area, in sq ft
Q = Volume, in cfm
V = Velocity, in ft/min

so that, still for sea-level conditions,

$$A = 773/13{,}200 = 0.0586 \text{ sq ft}$$

At altitude, it is necessary to supply larger volumes in order to retain the same mass flow. This results in higher velocities and, consequently, larger pressure drops which may be so high that it becomes impossible to obtain the desired volumes. For this reason, the area of the intake scoop must be calculated for the largest volume which may be required, namely the one at the cruising altitude.

Inasmuch as the resistance in the system at sea level was assumed to be 8.5″, it increases to 8.5 × 1.58 = 13.4″ at 15,000 feet. The ram pressure remains the same. This fact is based on the consideration that, for constant horsepower output, the speed of the plane increases with altitude until the ram of the less dense air equals that of the denser air. This is expressed by the following relation:

$$V_a = V_s\sqrt{d_s/d_a} \tag{8}$$

The pressure available at 15,000 feet, that is the ram pressure minus the pressure losses in the system, is then:

$$h_a = 19.4 - 13.4 = 6'' \text{ H}_2\text{O}$$

If this value is inserted into equation (6), with $d_a = 0.0475$, then:

$$V_a = 1096.5\sqrt{6/0.0475} = 12{,}350 \text{ ft/min}$$

As can be seen, the velocities at both sea level and altitude are very similar. However, since the volumes at altitude are increased, the area must be increased by the same ratio, which follows from insertion of the corresponding figures into equation (7):

$$A = 1220/12{,}350 = 0.099 \text{ sq ft}$$

The area of the intake must, therefore, be at least 0.1 sq ft in order to permit the supply of the required air quantities at the cruising altitude. (This calculation does not take into account the loss caused by the scoop itself. Normally, a correction factor has to be added which depends on the size, shape and frequently, the location of the scoop.)

High velocities not only increase the back pressure but also the air noise. For this reason, it is common practice to select the most desirable velocities for the individual branch ducts and calculate the necessary area by means of equation (7). Whenever feasible, the duct velocities should not exceed 3000 fpm although the need for keeping the duct size small may occasionally make higher velocities mandatory.

2.4 SIZE OF HEAT EXCHANGER. In specifying values for the size and weight of a heat exchanger, it must be borne in mind that, for given performance data, there are certain minima which cannot be improved upon, even with the most ingenious design. It can only be expected that the final values are as close to the theoretical optimum as possible.

The minimum size of a heat exchanger is determined by the area of the heat transfer surface which is necessary to transmit the specified amount of heat, if the inlet temperatures and the mass flow of both air and gas, as well as the temperature rise across the heater are given. This is evident from formula (1), namely:

$$H = U \times A \times \Delta t_m$$

In solving this equation for the area,

$$A = \frac{H}{U \times \Delta t_m}$$

in which A is the area of the transfer surface, in sq ft; H the heat amount to be transferred, in btu/hr; U the overall conductance, in btu/hr/sq ft/°F; and Δt_m the logarithmic mean temperature differential between the gas and the ventilating air.

H has been specified as 250,000 btu/hr. U and Δt_m must be calculated in the manner shown below.

2.41 *Calculation of Overall Conductance, U*—It will be remembered that:

$$1/U = L/k + 1/f_g + 1/f_a$$

in which k, the conductivity of the metal wall, is so high, and the thickness L so small, usually about $\frac{1}{32}''$, that the value L/K can be neglected. In other words, the metal separating the hot gas and cold air offers so little resistance to the heat flow that it is negligible in comparison to the resistance caused by the films.

The film coefficients f_g and f_a are computed from the formula:

$$f = \frac{0.027 \times C_p \times (\mu)^{0.2} \times (G)^{0.8}}{(D)^{0.2}} \qquad (9)$$

in which:

c_p = specific heat of the fluid;
μ = its viscosity;
G = mass flow rate;
D = the hydraulic diameter of the pipe or duct.

The calculation of the film coefficients and, for that matter, of the value U are very much facilitated by a method using three sets of curves which has been developed by G. B. Hodgson of the Solar Aircraft Company Research Staff. Hodgson divides formula (9) into two parts, designated M and O, and in such a manner that:

$$M = 0.027 \times c_p \times (\mu)^{0.2} \times 10^3$$

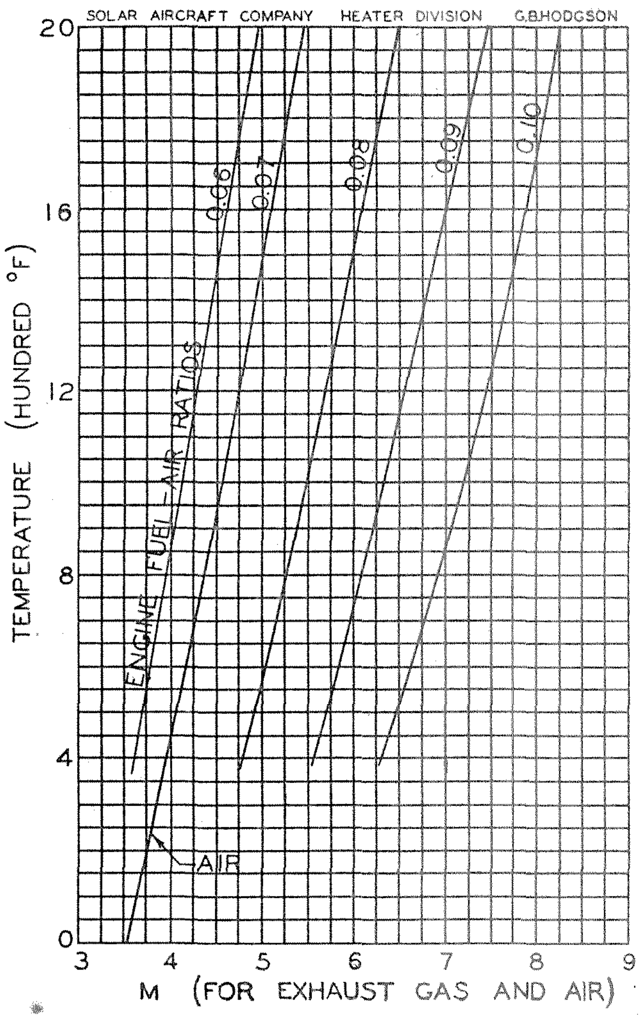

Fig. 83

and

$$O = \frac{(G)^{0.8} \times 10^{-3}}{(D)^{0.2}}$$

10^3 and 10^{-3} are added to M and O, respectively, in order to facilitate reading of the curves and cancel out, if M and O are multiplied with each other. Thus:

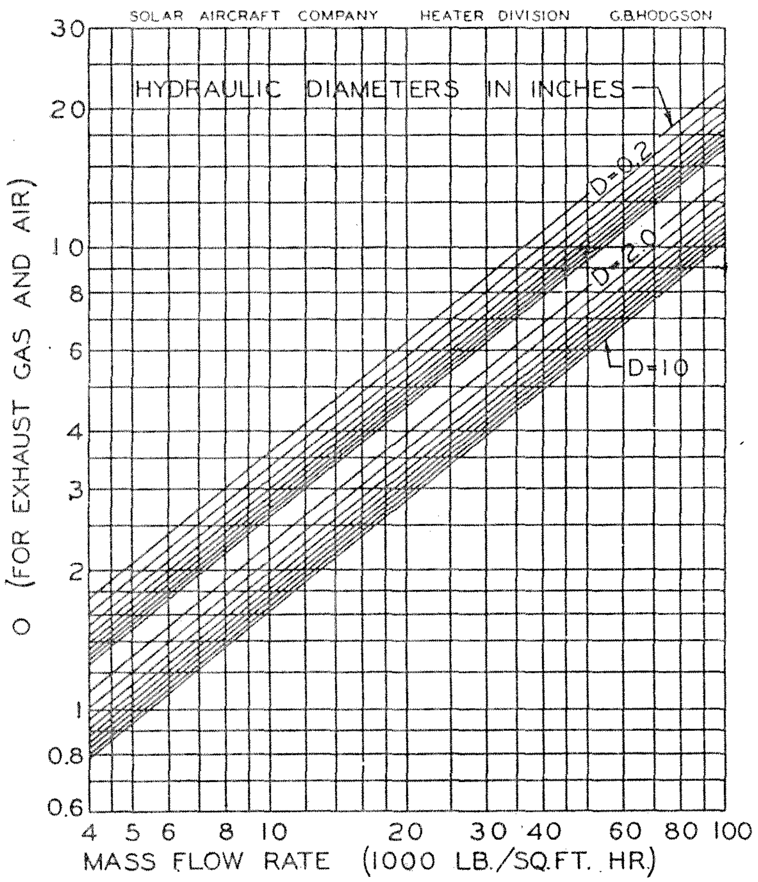

Fig. 84

$$f = M \times O$$

M can be determined from the curves in Fig. 83 in the following manner: M_g (exhaust gas) is read on the 0.07 line as this was assumed to be the specified fuel-air ratio. The average temperature of the exhaust gas within the heat exchanger had been found as 1524°. Therefore,

$$M_g = 5.0$$

M_a (air) is read on the same line since the values for air happen to coincide with those for gas at a fuel-air ratio of 0.07. The average temperature of the air within the heat exchanger is:

$$t_{am} = -60 + 300/2 = 90°$$

And so:

$$M_a = 3.6$$

The determination of the values for O which can be read from the curves in Fig. 84, is somewhat more difficult, since it is necessary to know the mass flow rates of the gas and the air as well as the so-called hydraulic diameters of their flow areas. The hydraulic diameter D is a function of the cross-sectional flow area A and the perimeter P. The latter is defined as the curve enclosing the flow area. Thus:

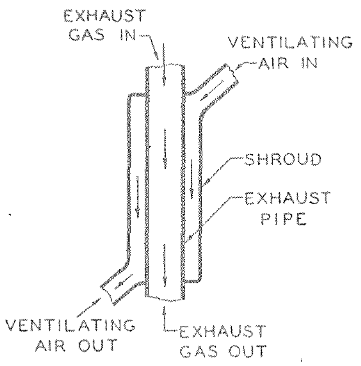

Fig. 85

$$D = 4A/P \tag{10}$$

In case of a round pipe or duct, the perimeter is $2\pi r$, so that:

$$D = \frac{4\pi r^2}{2\pi r} = 2r$$

Consequently, the hydraulic and actual diameters of a circular duct are identical. However, to obtain good heat transfer, it is desirable to make the hydraulic diameter as small as possible, that is, the perimeter very large compared to the enclosed cross section. This is usually accomplished by corrugations, *flutes* or similar methods of increasing the perimeter of the heat transfer surface.

Unless the design of the heater is known, it is necessary to assume a value for the hydraulic diameters, and it has been found that from 0.1 to 0.04 ft for both the gas and air sides is a fairly good approximation in most types of heat exchangers and within a wide range of outputs.

In order to carry out the calculation of a sample heat exchanger further, a design such as the one shown in Fig. 85 shall be selected. It consists merely of a shroud which envelopes the exhaust pipe and is the simplest, and not unusual type heat exchanger for small outputs.

The O.D. of the exhaust pipe was found to be 5.25″. At a wall thickness of 0.045″, the I.D. becomes 5.16″ which is also the hydraulic diameter of the pipe since it is circular.

The minimum area for the flow of the ventilating air had been established as $A_a = 0.1$ sq ft or 14.4 sq in. If the same value is used for the air flow area in the exchanger, the diameter of the shroud becomes, with A_{g1} as the cross-sectional area of the pipe:

$$d^2 = \frac{4}{\pi} \times (A_{g1} + A_a) = \frac{4}{\pi} \times (21.6 + 14.4) = 46$$

$$\text{and: } d = 6.75''$$

This allows for a ¾″ space between the shroud and the exhaust pipe. The perimeter of the air flow area is then:

$$P = \pi(6.75 + 5.25) = 37.7''$$

$$D_a = \frac{4 \times 14.4}{37.7} = 1.53''$$

This value for the hydraulic diameter is quite high which had to be expected due to the lack of corrugations or similar means to increase the perimeter.

It is now possible to establish the mass flow rates for the gas and air. The mass flow rate G equals the mass flow divided by the flow area so that, for the gas:

$$G_g = 2160/0.145 = 14{,}900 \text{ lb/hr/sq ft}$$

Similarly, the mass flow rate of the air is:

$$G_a = 3480/0.1 = 34{,}800 \text{ lb/hr/sq ft}$$

The values for O, as read from the curves in Fig. 84, are then:

$$O_g = 2.6$$
$$O_a = 6.5$$

Since the film coefficients equal the product of M and O,

$$f_g = 5 \times 2.6 = 13$$

and:

$$f_a = 3.6 \times 6.5 = 23.4$$

The value of U, the overall conductance, can now be found by means of the curves in Fig. 86, which were also provided by Hodgson. Thus,

$$U = 8.5$$

(Note that the exhaust gas film coefficient must be divided by ten to obtain the correct value on the curve.)

2.42 *Calculation of* Δt_m—In order to find the required area for the heat-transfer surface, it is further necessary to calculate the logarithmic mean temperature differential between the air and the gas in the heat exchanger, which is designated as Δt_m. As the air and gas pass through the exchanger, the temperature of the former increases while that of the latter decreases. This change is not arithmetical but progresses logarithmically since it is quite rapid, at first, and then tapers off gradually.

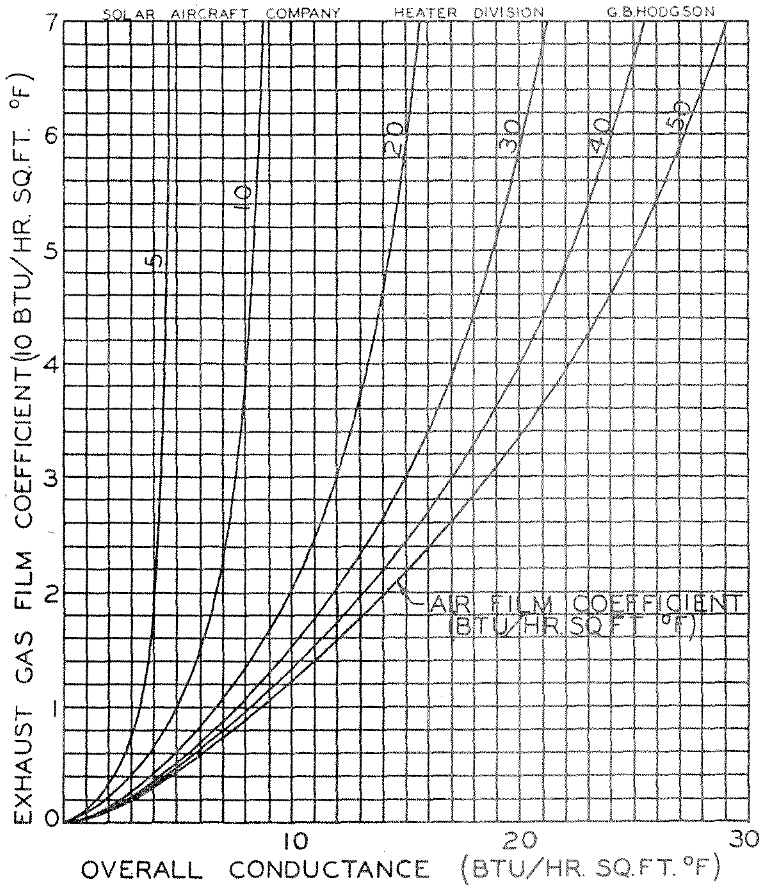

Fig. 86

Δt_m is, therefore, a function of the temperature differentials at the inlet, Δt_1, and at the outlet, Δt_2 and found by the following equation:

$$\Delta t_m = \frac{\Delta t_1 - \Delta t_2}{\ln \Delta t_1/\Delta t_2} \qquad (11)$$

Since the inlet and outlet temperatures of the gas and air are known, Δt_1 and Δt_2 can be easily computed.

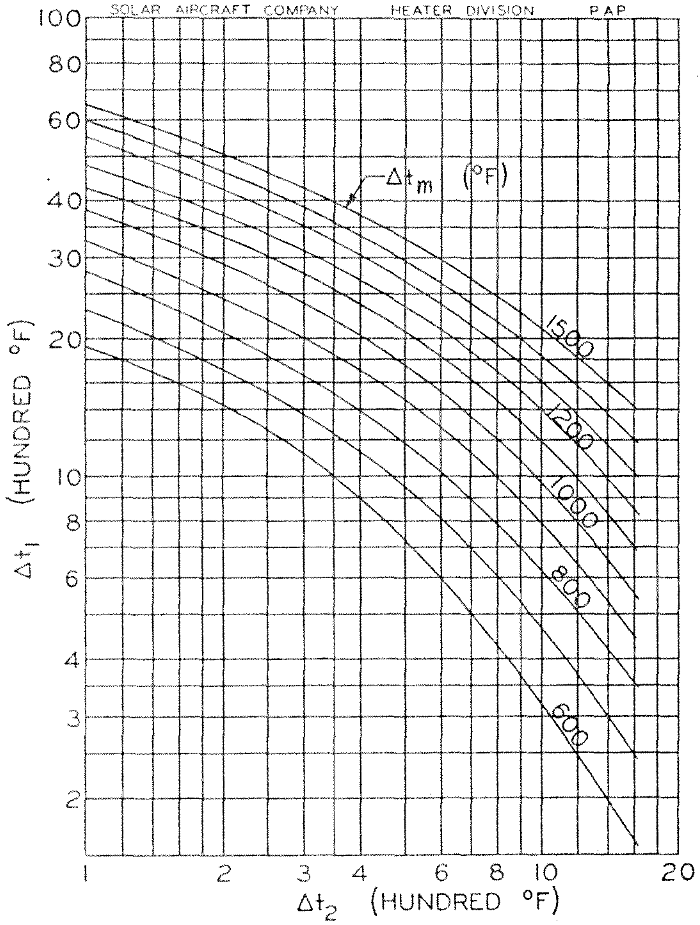

Fig. 87

$$\Delta t_1 = t_{gi} - t_{ai} = 1707 - (-60) = 1767°$$

$$\Delta t_2 = t_{go} - t_{ao} = 1341 - 240 = 1101°$$

The calculation of the logarithmic mean temperature differential is greatly simplified by a set of curves which is shown in Fig. 87. Δt_m can

be read directly from these curves as a function of Δt_1 and Δt_2, and yields, for this example:

$$\Delta t_m = 1400°$$

2.43 *Calculation of Dimension*—The calculation of the heat transfer surface can now be completed. Inserting the values found into equation (1), and solving for A,

$$A = \frac{250,000}{8.5 \times 1400} = 21.0 \text{ sq ft}$$

The length of the heat exchanger L is:

$$L = A/P_t$$

in which P_t is the thermal perimeter or that part of the air and gas perimeters which are common. In this example, P_t equals the circumference of the exhaust pipe, that is, $\pi \times 5.25 = 16.5''$, or 1.375 ft. Therefore:

$$L = 21.0/1.375 = 15.3 \text{ ft}$$

Such a value is, of course, prohibitive and shows that a straight shroud type of heat exchanger could not be employed for high outputs. Increase of the perimeters by a variety of methods is the main reason that the conventional length of presently used heat exchangers, of about 250 stu capacity, seldom if ever exceeds 24″.

3.0 Design Considerations

3.1 METHOD OF DESIGN. The preceding calculations for a sample heat exchanger serve merely to permit conclusions as to the general performance and dimensional data. At the same time, they form the basis for the design, in the course of which they are usually very much improved upon.

As had been shown, it is necessary either to make certain assumptions or to decide on a definite construction and temporary dimensions, in order to obtain the values for the flow areas, hydraulic diameters, etc. In actually designing the heater, the latter method is used and the preliminary values inserted into the formulas as given data. The results thus obtained are then checked against the desired values and corrections made.

In some cases, structural limitations make it necessary to specify a maximum allowable length, and the thermal perimeter may have to be increased until the required length is obtained. In another case, it may be found that the back pressures are too high. Then such dimensions as have a bearing on the flow resistance are changed, and the calculations are repeated. This again may result in decreased heat output which must now be compensated for by changing other dimensions.

This process is repeated until the most satisfactory compromise has been found and the designer is convinced that he has arrived at the optimum figures for this particular construction.

3.2 EFFECT OF PERIMETER. The most difficult problem in designing a heat exchanger is to get the necessary heat-transfer surface into the smallest possible space, both as to diameter and length, and to do so at a minimum of resistance to the flow of air and gas.

From the formulas and curves used in section 2.4 it follows that an increase of the air and gas perimeters results in a reduction of the hydraulic diameters, hence an increase in U, which brings about a reduction of the necessary transfer surface. By the same token, the subsequent increase of the thermal perimeter results in shortening the length of the exchanger. It must, therefore, be the goal of the designer to make the proportion of the flow area to the perimeter as small as possible.

This can be achieved in a number of ways. The simplest method consists of *corrugating* or *fluting* the heat-transfer surface. Such a design is indicated in Fig. 88, which shows a cross section of the previously calculated shroud-type exchanger. The dotted line represents the wall of the exhaust pipe, if it were fluted in such a manner as to retain the same flow areas for the gas and air as before.

Although only six flutes are provided, their effect on the hydraulic diameters and thermal perimeter is quite noticeable as is shown in the following.

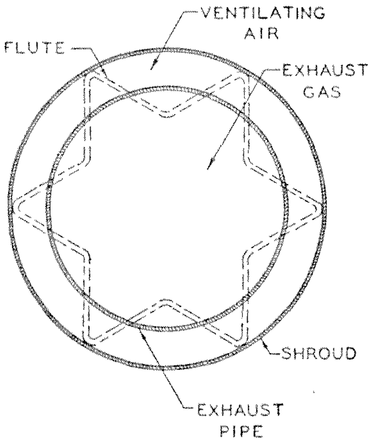

Fig. 88

The hydraulic diameter of the un-fluted exhaust pipe was identical with its I.D., namely 5.16″. The flow area was $A_g = 20.9$ sq in. The perimeter of the fluted pipe, as shown in Fig. 88, can be easily calculated and will be found to measure about 22.5″. Therefore, from formula (10):

$$D_g = \frac{4 \times 20.9}{22.5} = 3.72''$$

Similarly, the hydraulic diameter of the shroud was 1.53″ and its flow area $A_a = 14.4$ sq in. The perimeter consists of the circumference of the shroud, 21.2″, and the length of the flutes, 22.5″, so that it totals 43.7″. Consequently,

$$D_a = \frac{4 \times 14.4}{43.7} = 1.32''$$

Considering the fact that only six flutes are provided for, the reductions are indicative of the gain over the straight shroud construction. This applies also to the thermal perimeter.

P_t for the unfluted design was equal to the circumference of the exhaust pipe, namely, 16.5″. After the flutes have been added, the perimeter becomes:

$$P_t = 22.5'' = 1.875 \text{ ft.}$$

The effect of this increase shows itself very well in comparing the lengths of the two exchangers. The length of the straight shroud type was 15.3 ft. After fluting, the new length is computed by means of formula (11) as follows:

$$L = A/P_t$$

Assuming, for the sake of simplicity, that the heat transfer surface is the same as before, although it will be reduced somewhat due to the decrease in the size of the hydraulic diameters, the length becomes:

$$L = 21.0/1.875 = 11.2 \text{ ft.}$$

This length is not a sufficient improvement over the previous length of 15.3 ft to make it practical, but it is obvious now how the increase in perimeters will rapidly reduce the dimensions of an exchanger.

Another method of achieving this result leads to the tube type of heat exchanger. As seen in the cross-sectional view in Fig. 89, the exhaust gas is ducted through a number of tubes which are either

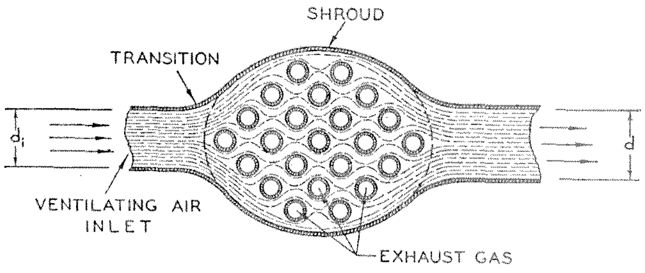

Fig. 89

circular or, more frequently, elliptical, while the air is passed over and between them. The tubes are connected by headers at both ends. Naturally, the ratio of area to perimeter is very favorable in a design of this kind.

In the plate-type heat exchanger, a number of parallel sheets of corrugated steel are arranged in such a manner as to alternate layers of gas and air, usually in cross flow. In other types, outside fins or inside plates, made from thin metal of high heat conductivity, are attached to the exhaust pipe to increase the transfer surface.

The main disadvantage of these and similar designs is the high resistance to the flow of air and gas which is unavoidable, if good heat transfer is expected. It is necessary, therefore, to arrive at a compromise between maximum allowable back pressures and optimum heat transfer, and it is here where the success of the heat exchanger depends on the ingenuity of the designer.

3.3 EFFECT OF FUEL-AIR RATIO on the heat output of an exhaust heat exchanger is not always fully appreciated. An increase of this ratio is usually connected with an increase in horsepower output. This, in turn, results in the following changes of equation (1):

$$H = U \times A \times \Delta t_m$$

U increases since the mass flow of the gas is greater for higher horsepower output (see Fig. 79). Δt_m, however, decreases because the inlet temperature of the gas drops with increase in percent of rated power beyond 60%, as can be seen from Fig. 80. The net result is either an increase of heat output for constant transfer area or a decrease of this area for constant heat output. The change in data with change of the fuel-air ratio becomes apparent in the following table for the previously calculated exchanger in which the values based on a ratio of 0.07 (first column) are compared with those based on a ratio of 0.1 (second column):

Fuel-Air Ratio	0.07	0.1
t_{gi}	1,707	1,520
Δt_1	1,767	1,580
Δt_2	1,101	1,060
Δt_m	1,400	1,320
G_g	14,900	26,200
M_g	5	7.6
O_g	2.6	4.0
f_g	13.0	30.4
U	8.5	13.2
A (Area)	21.0	14.6
L (Length)	15.3	10.6

Thus, the required area or length of a heat exchanger of given heat output can be very much decreased, if a higher fuel-air ratio is selected.

However, if the transfer area remains the same, an increase in the fuel-air ratio will raise the heat output considerably. For instance, if the ratio of 0.07, for which the sample exchanger had been calculated, should be increased to 0.1, its heat output will be increased from 250 stu to 336 stu, that is, by about 35%. (This value is found by repeating the previous calculations for the new temperature and flow rate of the exhaust gas.)

From the above, it can be concluded that tests at different fuel-air ratios will yield widely varying results. Therefore, if a heat exchanger has been designed for a higher ratio than that used by the customer, the unit may be rejected as not meeting specifications although it has proven entirely satisfactory during tests performed by the manufacturer.

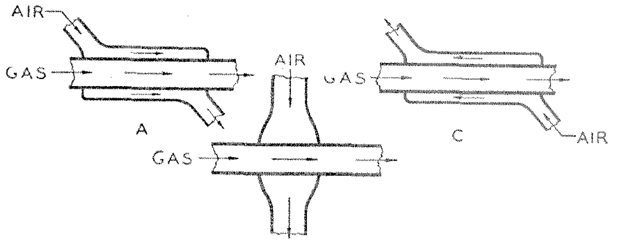

Fig. 90

For this reason, it is essential always to agree on the fuel-air ratio at which a heat exchanger is to deliver full, rated output. The value 0.07 appears to be very suitable for this purpose.

3.4 FLOW TYPES. The decision as to the design of the exchanger depends, to some measure, on the most suitable method for passing the air over the heat-transfer surface. This can be done in three general ways which are illustrated in Fig. 90; *A* shows the so-called parallel flow in which the ventilating air moves parallel to and in the same direction as the exhaust gas; *C* indicates the counter-flow type which is, essentially, also parallel flow but in opposite direction; *B* shows the cross-flow method in which air and gas move at right angles to each other.

There is not very much difference between these methods although cross flow is generally favored. The choice of the best suitable method in a particular case is usually based on installation requirements. In some instances, there may be no room for an elbow to lead the ventilating air into a cross-flow type of heat exchanger, and parallel flow is necessary. In another case, with definite obstructions to the use of a parallel or counter-flow heat exchanger, cross-flow is necessary.

The output for identical heat-transfer surfaces, mass flow and other design factors is nearly the same in all types. In spite of that, cross-flow types offer advantages in connection with the air distribution over the heated surfaces and are usually easier to design constructionally. This pertains primarily to the inlets and outlets for the ventilating air, and results in better weight-to-output ratios as will be shown shortly.

3.5 DESIGN DETAILS. The surfaces enshrouding the exhaust gas must be so designed as to withstand high temperatures, corrosion, shock and vibration. They are usually made from stainless steel of from 0.031″ to 0.038″ thickness. The air envelope is made from the same metal in order to permit proper welding. The thickness is somewhat less, normally about 0.025″. Flanges and other means of attachment must be designed to support the exchanger with its connecting ducts and piping under all stresses experienced on an airplane.

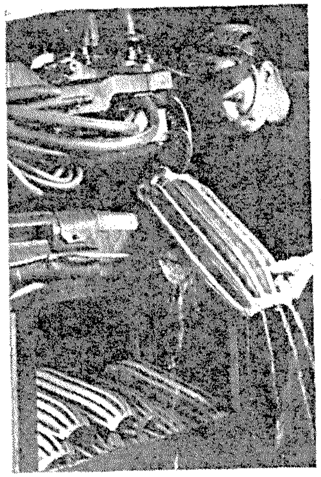

Fig. 91

The forming and welding of the compound components of a heat exchanger is an art in itself, and the difficulties to be expected in production and service must be another consideration of the designer. Figure 91 shows one phase in the manufacture of a Solar Aircraft heat exchanger of the flute type. The individual flutes are formed under a drop hammer and seam-welded together as illustrated.

Other design considerations, such as the means to prevent infiltration of CO, have been discussed in Chapter XIII.

4.0 Performance at Altitude

All calculations made previously were based on the assumption that, at constant horsepower output and mass flow, the heat output of the heater would remain constant. This assumption is correct only if the outside ambient temperature remains constant too.

In designing a heater, it is necessary to base the calculations on a given D.O.A.T., and a likewise given temperature rise across the heater. If the actual outside temperature is higher than the D.O.A.T., which will be the case usually, the temperature of the ventilating air increases correspondingly unless a compensation is made. This is not very easy for exhaust-air heaters because the mass flow of air through them should remain constant to prevent overheating. Therefore, a certain amount of the hot air is spilled overboard by means of a spill damper and a similar amount of cold air mixed with the remaining hot air. In this manner, constant mass flow through both the heat exchanger and the ventilating ducts is assured while the heat content of the ventilating air can be changed at will.

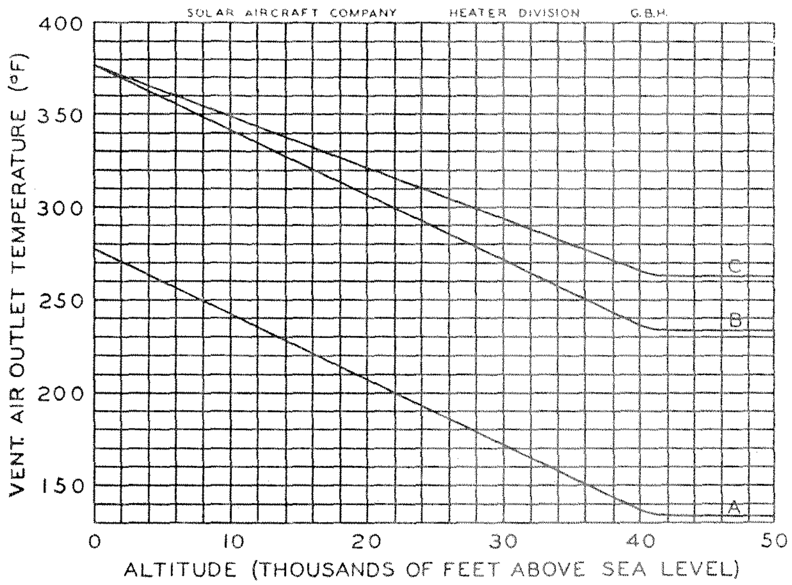

Fig. 92

The need for such regulating means becomes obvious, if the plane is subjected to a variation of outside temperatures as would be the case in climbing or descending. The average temperatures at various altitudes have been shown in Fig. 37. If these values are encountered instead of a constant D.O.A.T., the outlet temperature of the ventilating air will decrease with altitude as shown in Fig. 92. Curve *A* represents the air temperatures for a constant rise of 200° across the heat exchanger, and curve *B* the corresponding values for a temperature differential of 300°. These curves are quite significant in determining the most desirable rise but hold true only if the rise can be assumed as constant for change in altitude.

This, however, is not the case as can be seen from a study of equation (1), namely:

$$H = A \times U \times \Delta t_m$$

The area A does not change with altitude, of course. The overall conductance U changes with the film coefficients which, in turn, are determined by formula (9):

$$f = \frac{0.027 \times c_p \times (\mu)^{0.2} \times (G)^{0.8}}{(D)^{0.2}}$$

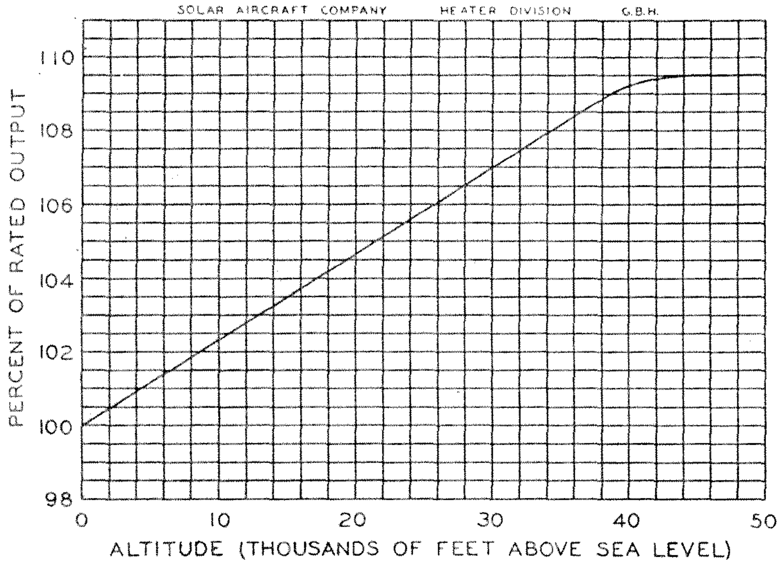

Fig. 93

The specific heat c_p changes with temperature but not sufficiently within the temperature difference from sea level to altitude to be of consequence. The change of the viscosity μ with the exponent 0.2 is also insignificant. The mass flow rate G remains constant as does the hydraulic diameter D. Consequently, f and, therefore, U can be said to be practically constant for changes of density and moderate changes of temperature.

Δt_m is a logarithmic function, so that it increases faster the greater the temperature differential is. Since the inlet temperature of the ventilating air decreases with altitude, the temperature differential between the air and gas at the inlet increases and, with it, Δt_m, so that H actually increases with altitude for constant engine power. This is not surprising since, with a larger temperature differential, more heat is available for transfer. Using again the analogy of two different water levels, the pressure head can be increased by either increasing the height of the higher level or decreasing that of the lower one.

Consequently, the heat output of a heat exchanger will increase with altitude, even if all factors with exception of the outside temperature remain constant. This increase is shown in Fig. 93. The curve has been plotted for a 300 stu heater, by assuming a decrease of temperature with altitude as indicated in Fig. 37, and a temperature rise across the heat exchange of 300° at sea level.

The percentage of increase is not very high; it amounts to only 7% at about 30,000 feet. Nevertheless, it should be taken into account during the ground tests, for a heater tested at room temperature will yield lower outputs than if the ventilating air is chilled before entering the exchanger.

The corrected, actual outlet temperature for a 300° rise at sea level is shown by curve C in Fig. 92. As can be seen, the drop with altitude is somewhat less than in curve B for which the heat output was assumed to remain constant. The mass flow is identical and constant in both cases.

As a rule, neither the change in outlet temperature nor the small increase in output at altitude warrant particular consideration during design since the final performance characteristics depend on so many variables that the designer must allow himself a considerable margin anyway. In operation, the required outputs and air temperatures are obtained through proper means of regulation which can be built to any desired degree of accuracy.

5.0 WEIGHT

Calculation of the weight is not difficult, if the design and dimensions of the heater are known. For instance, the weight of the shroud-type heat exchanger, discussed in section 2.4, can be found on the basis that both the exhaust pipe and the shroud are made from stainless steel, and that the thickness of the former is, for instance, 0.045″ and of the latter 0.035″. About 10% of the calculated weight should be added for attachments and transitions. (Considerably lighter materials are being used in recent designs, as pointed out in section 3.5.)

However, if it is desired to arrive at an approximation for the weight of a heater of which only the general specifications but no design features are known, the previously cited figure of one lb per 10 stu will be found to apply within a wide range.

In general, the weight-output ratio depends on the flow type and the horsepower for which the exchanger is designed as shown in Fig. 94. The ratio is usually less favorable for parallel flow than for cross flow since the former requires more complex ducting and fairing into the shroud surrounding the heater.

The values for the horsepower, referred to in Fig. 94, are those used during the design of the heater. The ratio decreases with increase in horsepower. This is not surprising since a larger mass flow rate of exhaust gas permits better utilization of space and heat.

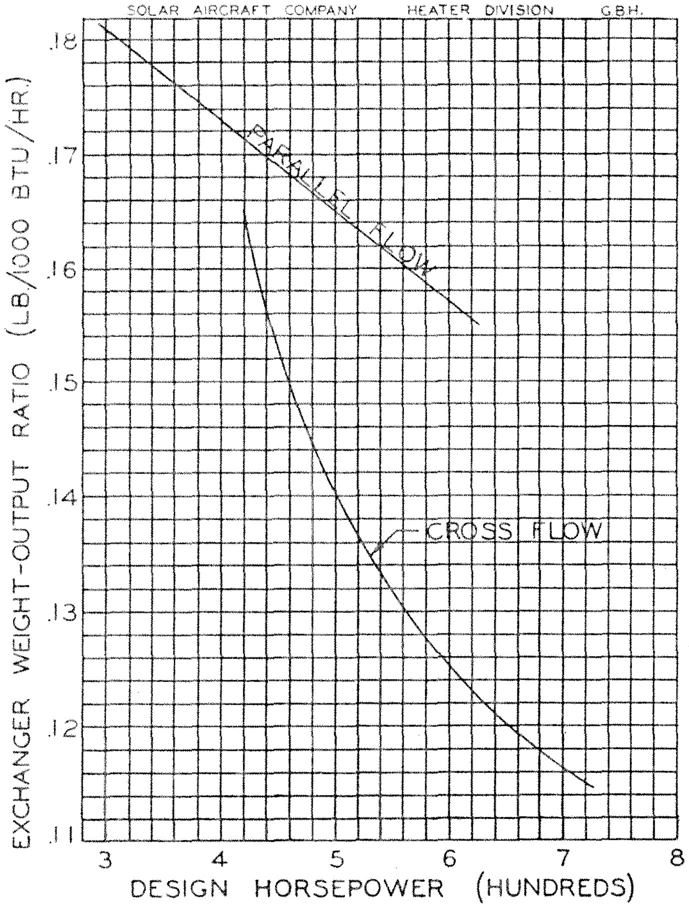

Fig. 94

The curves in Fig. 94 are based on empirical values and do not necessarily represent all or most types of heat exchangers. However, they give an indication as to the relative change of the weight-output ratio for different types of flow and changes in horsepower.

6.0 Representative Designs

The importance of exhaust-gas heat exchangers is best illustrated by the fact that an increasing number of prominent manufacturers is producing heaters of this type, and usually, models for widely varying applications.

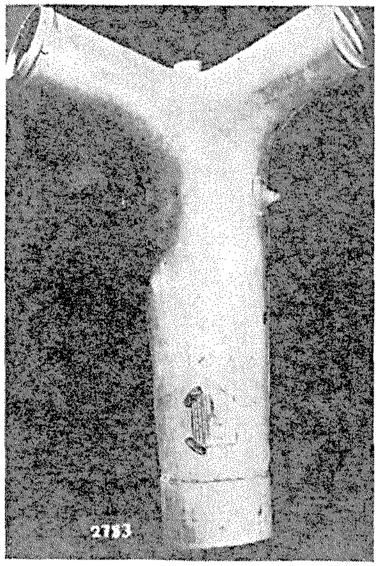

Fig. 95

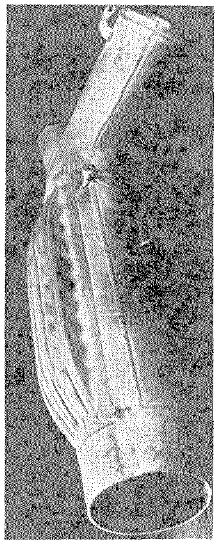

Fig. 96

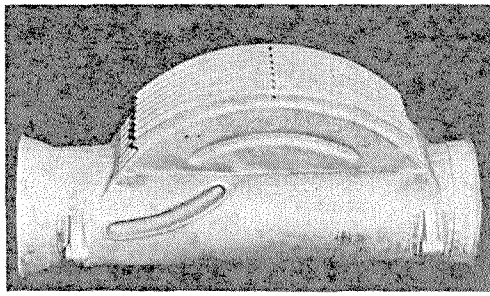

Fig. 97

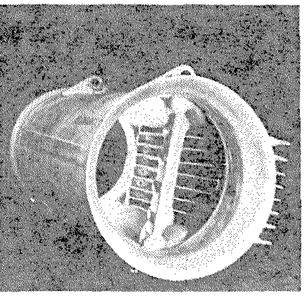

Fig. 98

Solar Aircraft Company found heat exchangers to be a very desirable product and has contributed several successful models most of which were designed by a young experimental engineer, P. A. Pitt.

Figures 95 and 96 show two views of an early Solar exchanger for fighter planes. Flutes are welded to the exhaust pipe shortly behind the point at which the legs from the two engine ports join. Air is passed over and through the flutes, and thus heated. The efficiency is rather low.

A later development is illustrated in Figs. 97 and 98. Here the flutes are not only considerably enlarged and hollow but a baffle is provided which diverts part of the exhaust gasses through the flutes. The efficiency of this exchanger is considerably higher than in the previous one. Figure 99 is a photo of a typical fluted heat exchanger. The shroud enveloping the air is omitted. Figure 100 shows another design of a flute-type exchanger.

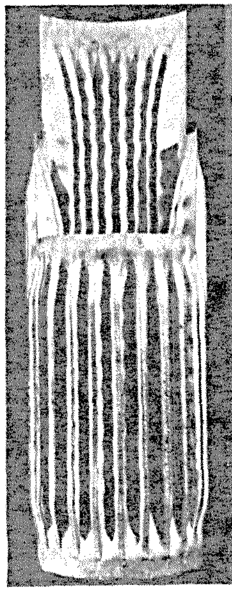
Fig. 99

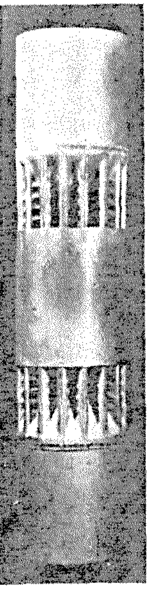
Fig. 100

The models illustrated so far are all parallel-flow exchangers. Disclosure of the details of Solar's newest cross-flow exchangers is not possible at this time. However, Pitt provided the data for plotting the curves shown in Figs. 101 through 104, which show the performance characteristics of one of his latest designs. This particular exchanger is rated at 300 stu and weighs approximately 30 lb which conforms very well with the requirement of 1 lb/10 stu. Figure 101 gives the ventilating air-flow rate for different heat outputs. At 300 stu, the rate is 3300 lb/hr. The pressure drop at this rate can be read from Fig. 102 and yields 2.25" H_2O. This is considerably better than the previously specified 1" per 1000 lb of air.

The exhaust-gas flow rate for 300 stu is found from the curve in Fig. 103 and shows that 3150 lb/hr of gas are required. Finally, Fig. 104 yields the pressure drop for this rate which is 2.6" H_2O. Inasmuch as up to 1.5" should be allowed for every 100 stu, this exchanger is very much below the permissible maximum.

It will be noted that the exhaust-gas flow was kept constant in measuring the data for the ventilating air and vice versa. The corresponding values are noted on the figures.

Curves of this kind assist in presenting the characteristics of a heat exchanger in the best possible manner and in giving an overall picture of its performance. Therefore, they should always accompany the test data.

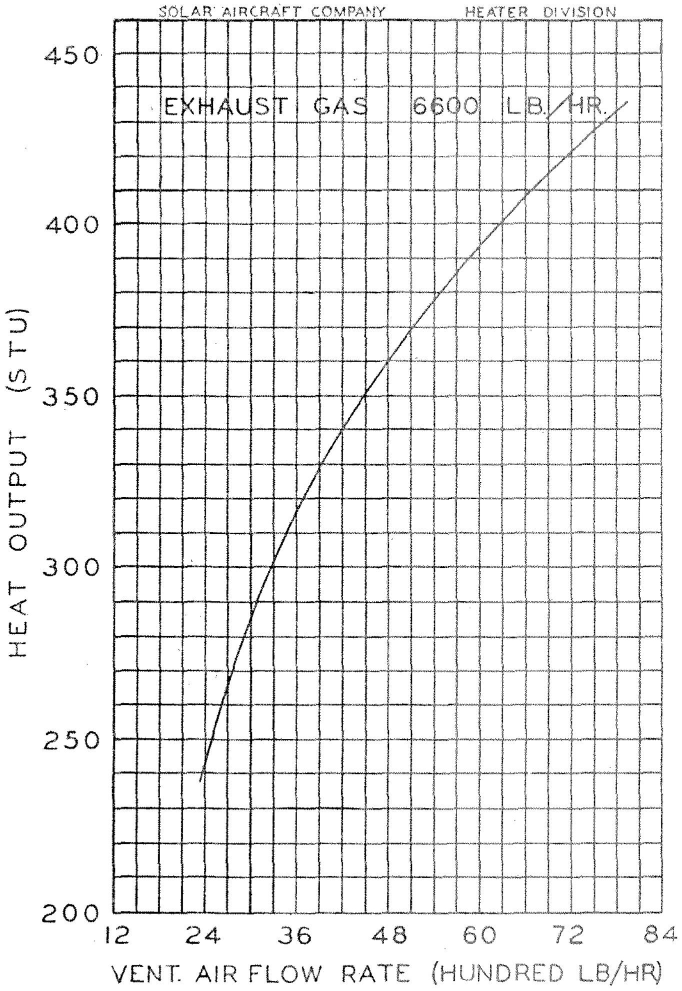

Fig. 101

A typical example of a cross-flow heat exchanger is the Stewart-

Warner heater shown in Figs. 105 to 107. Realizing the usefulness of such heaters for many purposes, Stewart-Warner has added them to their extensive line of internal-combustion heaters which had been discussed before.

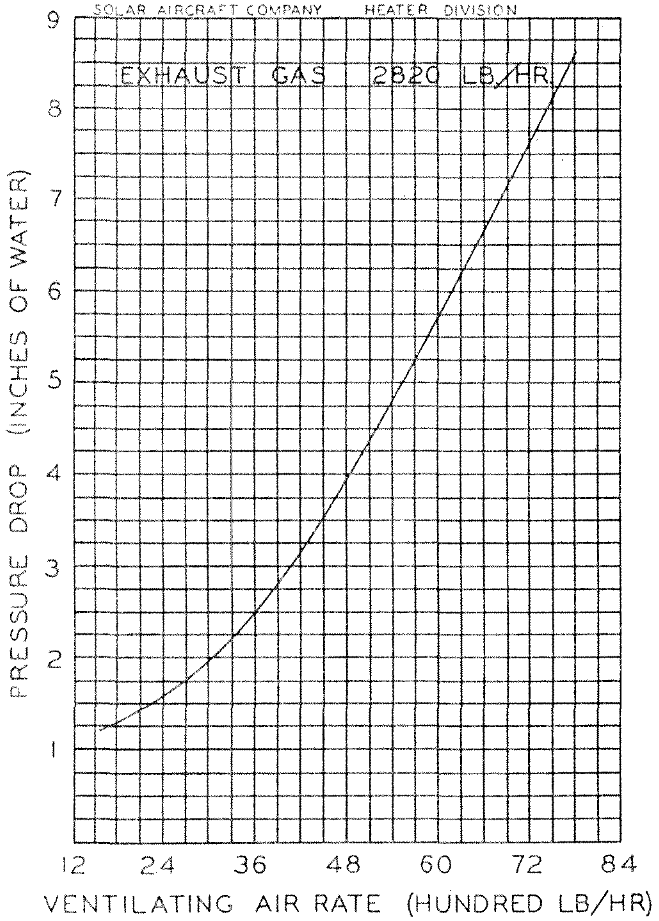

Fig. 102

The heater shown has a rated capacity of 250 stu and is of the tube type. Figure 105 gives a cross-sectional view of the elliptical tubes through which the gas passes. The side-view in Fig. 106 illustrates the arrangement of the tubes and the spaces through which the air travels in cross-flow. Figure 107 shows the complete heater, including the transitions for attachment of air ducts and exhaust pipe. The wires visible between the legs connect to thermocouples which measure the temperature gradients within this particular unit. The heater is so designed as to permit rapid removal of the shroud for inspection and service. It demonstrates, convincingly, the simplicity of the cross-flow heat exchanger and the well-distributed flow of the air over the heat-transfer surface.

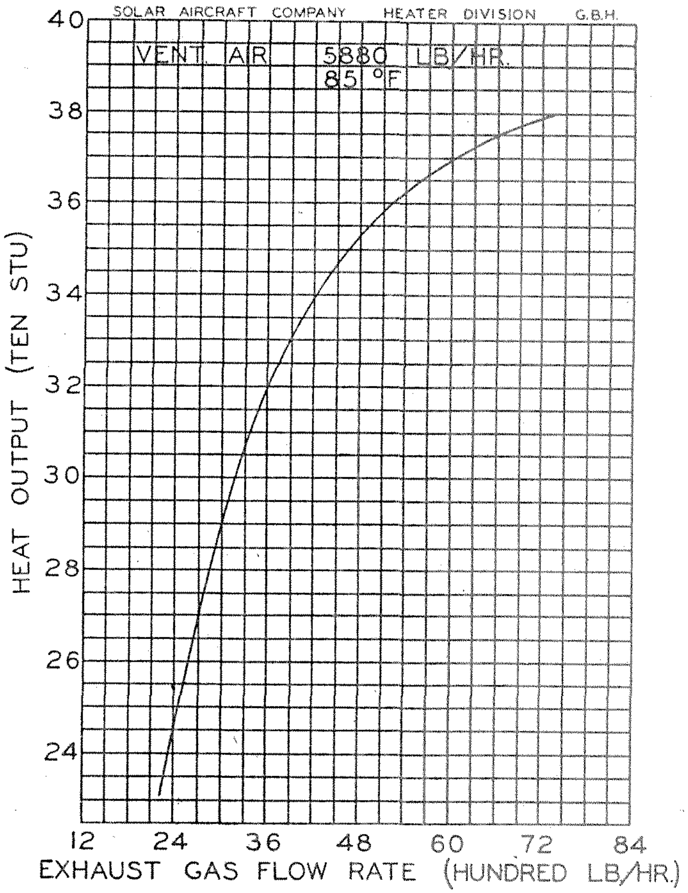

Fig. 103

Although exhaust-gas heat exchangers need further development, it can be safely predicted that they have a practically unlimited future. However, the only fact which will be known for some time to come, about designs which are now restricted or still in the laboratories, will be that they have met all of the heat requirements on military airplanes, no matter how high they are. Ground heating will remain the only task which must be accomplished by supplementary systems, such as internal-combustion heaters.

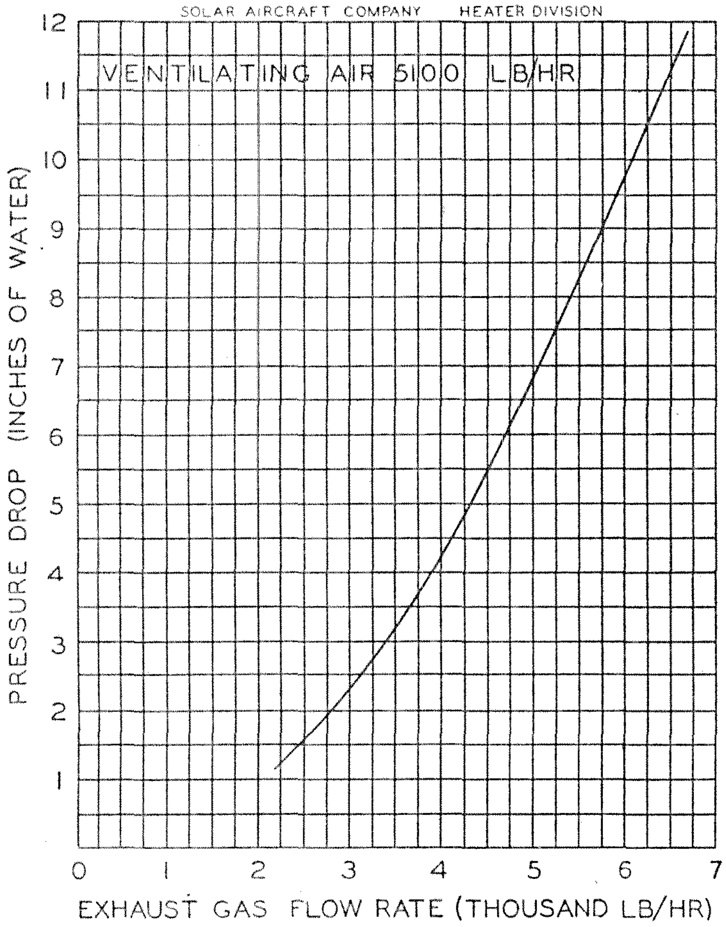

Fig. 104

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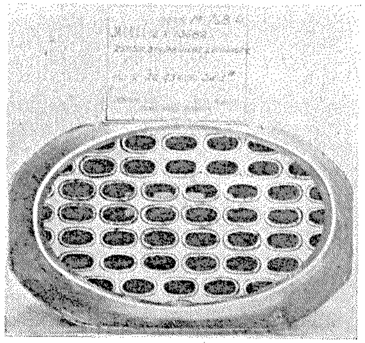

Fig. 105

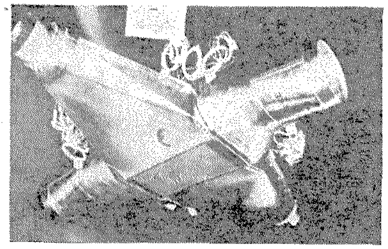

Fig. 107

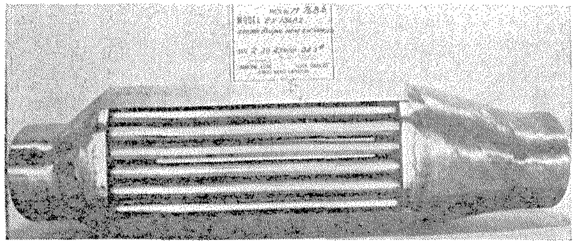

Fig. 106

XVII

SELECTION OF HEAT SUPPLY

The proper selection of heat supply for an airplane requires knowledge of (a) its heat requirements; (b) the means with which to meet these requirements and, (c) the methods to be employed; (a) and (b) are based mainly on technical considerations which have been discussed in the previous chapters. (c) is governed by factors which can not be calculated but must be found in accordance with existing conditions, after (a) and (b) have been established.

Consequently, the following steps are necessary before the heat supply for a particular installation can be decided upon: (1) Study the airplane, its lay-out, functions and performance data; (2) Establish the individual tasks of the heating system, for instance, cabin heating, anti-icing, accessory heating and such others as will increase the efficiency of the airplane and its crew; (3) Determine the fundamental design data for calculation of the heat requirements: temperatures, temperature differentials, maxima and minima, and air quantities; (4) Calculate individual and total heat requirements.

After these steps have been completed, the designer can proceed to (5) select the best suitable heating scheme and (6) select the best suitable heating system. The final steps are then to (7) write specifications and (8) procure equipment.

This chapter deals with the last four steps.

1.0 Selection of Heating Scheme

The selection of the heating scheme concerns the choice between central heating, spot heating or a combination of both. All three schemes have definite advantages for certain purposes which are discussed in the following:

1.1 SPOT HEATING is accomplished by means of individual or unit heaters which generate the heat at the point of application. Their capacity is normally low and varies from 10 to 20 stu. Somewhat higher capacities are required in special cases, for instance, heating of a gun breech in a non-pressurized turret which is fully exposed to the cold wind.

Unit heaters may be entirely self-contained and automatically operated, or receive their fuel-air mixture and even the ventilating air from a central source. Ducts, fuel lines and exhausts may be wholly or partally manifolded, or individual. Similarly, control of a series of unit heaters can be central, individual or automatic.

Spot heaters are ordinarily either of the internal-combustion type or electric. The former are employed extensively for personnel heating of cockpit and cabin-type planes and for the heating and pre-heating of accessories. The latter are used mainly for equipment heating and galley applications.

Spot heating is being rapidly replaced by central heating and will remain useful only for the heating of accessories to which it is impractical to duct heat from a central source.

Pictures of typical unit heaters have been shown in Chapter XV. A somewhat different model of a spot heater is illustrated in Fig. 108. This is a Stewart-Warner internal-combustion heater, and differs from other heaters of this type as it has no heat exchanger. In addition, its blower is operated by a hand crank, thus supplying air for combustion and additional air which is mixed with the products of combustion. In this manner, a large volume of hot air is provided for local application. The heater has its own gasoline tank and needs no outside connection whatsoever. Its main purpose is to provide spot heating of accessories on the ground and move it quickly from one point to the other without requiring the moving of electric, fuel or air lines.

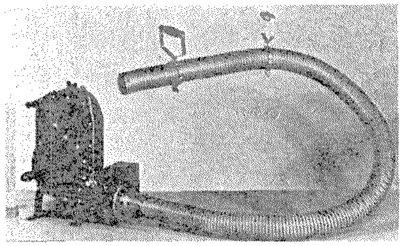

Fig. 108

Electric spot heating is usually accomplished by means of *shoes* which are slipped over the part to be heated. These shoes or covers are made from fireproofed fabric interwoven with heating wires as discussed in Chapter XIII. Heating coils with fans mounted in back of them are not favored on account of their large current consumption.

1.2 CENTRAL HEATING is that which serves two or more outlets normally located at a distance from the source of heat. This method is the usual choice, if heating and ventilating are combined, and if both heat and air must be supplied in large quantities and at a number of places throughout the plane.

The advantages of central heaters are the following: They are usually located outside of the cabin. They require only one source for the supply of air, current and, in the case of internal-combustion heaters, fuel. Therefore, their control is greatly simplified. The ratio of heat output to weight is very favorable. Servicing of central heaters can be done more efficiently and faster than of a series of unit heaters.

On the other hand, if a central heater fails, the entire heat supply is cut off, and serious damage may result to such accessories which have been designed with the assumption that they would be properly heated at all times. Under present conditions, failure of a central heating plant may conceivably put a large, military plane out of action.

A further and most complicating disadvantage of central heating systems is the need for extensive ducting. Many planes of the cabin type are unsuitable for ducting. In spite of that, it will be found that the incorporation of anti-icing, anti-frosting and heating of a growing number of accessories necessitates the installation of ducts or flexible hoses. Therefore, the need for ducting should not influence the designer in his choice for or against central heating.

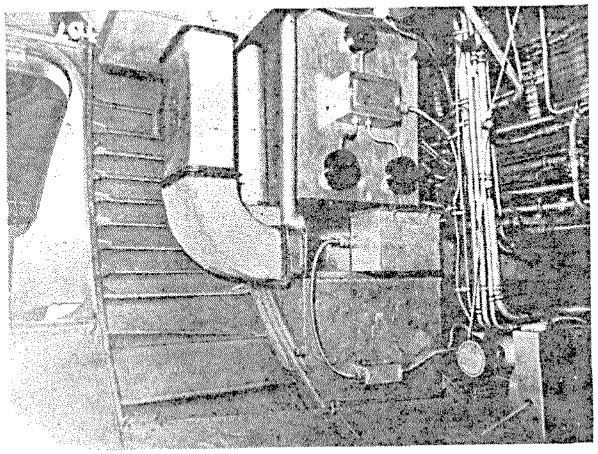

Fig. 109

Typical central heaters have been described in the previous chapters on heat supply. Figure 109 shows the installation of a central heater of the early, internal-combustion type in the Curtiss-Wright CW-20 transport which was the prototype for the famed C-46 Commando. As can be seen, a large rectangular duct leads from the heater into the cabin where it divides into branches to various outlets. The control board for this heater was located in the flight deck.

1.3 COMBINATION SPOT AND CENTRAL HEATING. The complexity of heat supply on modern airplanes, particularly military craft, makes it quite difficult to supply all heating needs from one large source. Although central heating is usually favored for all but cockpit-type planes, the disadvantages of this method become quite serious the larger the cabin is. The installation of ducts of sufficient size to carry enough air and heat from the central source to every point of distribution often results in unsurmountable difficulties. The danger of failure of the entire heat supply, if merely an igniter in the heater burns out, is another disturbing factor. Finally, there are many applications for which spot heating is more effective, if not mandatory.

For these reasons, a combination of both spot and central heating is normally the advisable method. On large planes, there should be, in addition, at least two central heating plants which are entirely independent of each other, so that, if one of them fails, the other one can take over at least a reasonable part of the functions. This method is quite common in exhaust-heating systems in which heat exchangers are normally attached to the exhausts of two different engines, thus constituting two independent sources of central heat supply.

Occasionally, a third central heater of the internal-combustion type is installed in the aft section to provide empennage heating during flight and heating of the entire airplane on the ground. Supplementary spot heating is taken care of by small internal-combustion or electric units.

2.0 SELECTION OF HEATING SYSTEM

Summarizing the advantages and disadvantages of the heating systems discussed before, the following recommendations are made for the selection of the most suitable method:

2.1 ELECTRIC HEATING is recommended for the heating of such accessories which can not be easily reached by ducting or piping, such as propellers or the pitot static heads of the air-speed indicators, or which require localized and well-regulated heat, such as cameras, gun sights and lenses. Electrically-heated flying suits are very advantageous for personnel heating in cockpit-type planes or in exposed portions of larger planes which are not suitable for duct heating, such as swiveling gun turrets. For galley requirements electric hot plates are preferred to other means of galley heating, as are electrically heated covers for equipment of small size. Electric heating is so extremely simple, efficient and controllable, there is only one limiting factor in its selection, and that is not so much the current consumption as the weight.

In view of the advantages of this heating method, it would be easy to provide for larger storage batteries or generators were it not for the excessive weight of such apparatus. According to an interesting analysis by Vernon H. Grant,[1] it takes 108 lb to store enough electric energy to produce one kw for one hour. One kw is equivalent to 3415 btu/hr, so that electric heating adds a weight of 1 lb for every 35.1 btu/hr. Since this is based on 100% efficiency and does not take into account the weight of the electric heater itself—although this is very small—a weight-to-heat output ratio of 1 lb/0.03 stu is a more probable figure. Comparing this to the previously mentioned ratio of 1 lb/10 stu for other types of heaters, demonstrates the large loss in weight which electric heating entails.

On the other hand, these figures are conclusive only for comparatively large heat outputs. The weight-to-heat output ratio of exhaust and combustion heaters becomes increasingly unfavorable with smaller heat outputs and, at a capacity of 10 stu, it increases to 1 lb/1 stu and more. Adding to the weight of the nonelectric heater that of the ducting, diffusers and other transfer components, it becomes evident that electric heating is just as cheap or even cheaper, in terms of weight, for *small* outputs. Another important consideration is that electric heaters are usually in close contact with the part to be heated so that the overall efficiency is far greater than that of blast heating. It will always pay to select electric heating for net requirements below 1 stu.

2.2 EXHAUST-GAS HEATING. As will be remembered heat can be extracted from the exhaust gas of the engine in several ways, namely by means of exhaust air heaters, exhaust steam heaters, and exhaust liquid heaters.

2.21 *Exhaust Air Heaters* are, essentially, central heaters suitable for the supply of large heat quantities. They are particularly favored for anti-icing of wings, anti-frosting and for cabin heating. Equipment heating is, at present, confined to the accessory section of the engines, or such accessories which are located inside the cabin.

Ducting to remote outlets is not desirable. For the same reason, empennage heating is feasible mainly in planes of medium size. Ground-heating is not possible unless an engine can be idled. As a rule, exhaust air heaters should be selected where large heat quantities are required during flight and where extreme simplicity of the heating plant is an important factor.

2.22 *Exhaust Steam Heaters* have been largely replaced by other heating systems, although there are still a number of installations in use on transports. The weight, service requirements and other disadvantages of steam heating have proven a handicap in military operations and more than offset its advantages.

One of the principal features of steam heating is the fact that it lends itself very well to accessory heating. The lines carrying the steam or hot condensate can be easily coiled around equipment, or provided with fins and framed around large, flat areas which have to be heated. However, in spite of this advantage, exhaust steam heaters are not favored for military airplanes and have probably only a limited future in post-war, commercial aircraft.

2.23 *Exhaust Liquid Heaters* share not only most of the disadvantages of steam heaters but their weight-to-heat output ratio is very unfavorable. They have been used for accessory heating and galley requirements, however, their general consideration as a major source of heat supply is not recommended.

2.3 INTERNAL-COMBUSTION HEATERS are very suitable for spot heating, particularly at locations which are not easily accessible. They are also practical for the anti-icing and heating of the empennage section of large aircraft. Many central heating systems employ internal-combustion heaters throughout, although exhaust air heaters are beginning to replace the former for the anti-icing of wings and cabin heating.

Fig. 110

The main advantage of these heaters is their portability and independence from the airplane. This makes it possible not only to locate them in any convenient part of the airplane but also to operate them on the ground. If equipped with their own engine, they do not even need supply of electric current.

Although the weight-to-heat output ratio is the same or, sometimes, even more favorable than that of exhaust air heaters, they are more complex and difficult to operate. Ignition and operation at altitude is often a problem. These disadvantages, however, can be minimized by proper design.

2.4 GROUND HEATING can be accomplished in two ways, namely either by means of outside or integral heaters.

2.41 *Outside, Ground Heaters* are provided at regular landing fields as part of the ground air-conditioning equipment which had been discussed before. Figure 110 shows a standard Delco oil-burning furnace in one of United Air Lines' air-conditioning trucks. The capacity of the heater is 250 stu. It is operated by a power take-off from the truck motor.

Such heaters are suitable only for commercial operations. Military planes are heated merely enough to keep or make the plane operative for immediate take-off even after lengthy stays on the ground during cold weather. Outside, ground heaters for this purpose are mainly used for engine pre-heating, and are fired by gasoline or propane.

2.42 *Integral Ground Heaters* are to provide heat to the plane, its occupants and accessories on the ground, independent from any outside sources. This is often of considerable importance to military planes which may be exposed to cold ground winds for many hours yet must be ready for take-off at a moment's notice or may also have to serve as living quarters for their crew, with no outside sources of electric current or heat available.

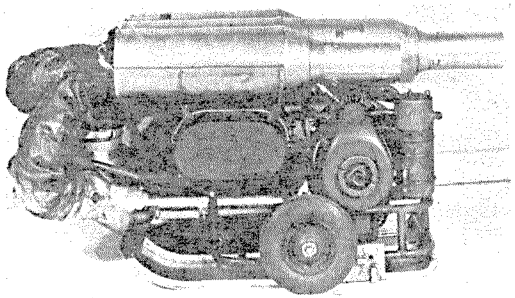

Fig. 111

At this writing, most integral ground heaters are of the internal-combustion type, sometimes with a small engine to drive the blower and furnish electric power. The Stewart-Warner ground heater, shown in Fig. 111, is an example of such a unit. It is completely self-contained, weighs 183 lb and requires no connections to the outside or the airplane. It is mounted upon a sled, equipped with rubber wheels and can be installed in the plane as an integral component, or removed and used as an outside heater. The fuel is regular aviation gasoline.

The choice between outside and integral ground heaters often determines the choice of the main heating plant. If an integral heater is necessary for ground operation, it is usually feasible to use the same heater during flight in order to avoid duplication and unnecessary weight. For this reason, internal-combustion heaters are occasionally preferred to exhaust air heaters, although the latter might be more suitable as flight heaters in a particular installation; both systems may be used together during flight, with the internal-combustion heater alone taking care of the limited heat requirements on the ground.

3.0 Selection by Comfortization Type

The final consideration in the selection of heat supply is the purpose and type of airplane in which it is to be installed. Unfortunately, there are so many combinations between the comfortization types, military and commercial applications, requirements of ground heating and others, that it would be futile to attempt the establishment of fixed rules, and much must be left to the common sense of the designer.

There are, however, a few considerations which may serve as a general guide.

3.1 COCKPIT TYPE

3.11 *Non-military.* Heating of non-military airplanes of the cockpit type is frequently not necessary but always desirable. Heat supply may be furnished by a small exhaust air heater or a spot heater of the internal combustion type. The latter are somewhat lighter and more efficient for planes with engines of small power.

As a rule, neither anti-icing nor ground-heating is required.

3.12 *Military.* Cockpit heating should be provided under all circumstances by means of either an exhaust air or internal-combustion heater. The former is preferable if it is necessary to furnish heat also for anti-icing and equipment or if two individual cockpits have to be heated.

Internal-combustion heaters are favored in case ground heating is specified which is not the rule in such planes. Sometimes, a combination of a combustion heater for cockpit and ground heating, and an exhaust air heater for anti-icing will prove very practical.

Electric flying suits are recommended for cockpit-type planes flying at high altitudes and low temperatures.

3.2 CABIN TYPE

3.21 *Non-military* cabin-type planes are usually private planes used for long distance travel at medium altitudes. Again, the choice between an exhaust air heater or an internal-combustion type spot heater is a matter of opinion. The former is somewhat simpler for the private owner to operate; the latter provides ground heating which may occasionally be desired.

Heating of wings and accessories is normally unnecessary. However, if a special use of a plane requires means for ice-removal, an exhaust air heater should be selected. In this connection, it should be remembered that engines of low horsepower rating make it difficult to obtain satisfactory heat extraction from the exhaust.

3.22 *Military* cabin-type planes are considerably larger than their non-military equivalent: They are medium bombers and transports which carry a crew of about five persons and a considerable amount of armament and equipment which must be heated. Altitudes and speeds are high so that the outside temperatures and heat losses become important factors. In addition, planes of this type are usually very little or not at all heat-proofed.

Due to the very large infiltration of cold air and the difficulties encountered in installing a ducting system, spot heating has been preferred up to this time. Heaters for this purpose are of the internal-combustion type and located near the persons or equipment to be heated. For flying at very low temperatures use of electrically-heated flying suits is often more adequate.

The heat requirements which have been added by the need for anti-frosting of windshields, bombsights and cameras, for anti-icing and for the heating of gun breeches, ammunition, cameras and similar equipment, make the installation of a central heater mandatory. The trend appears to be towards the use of exhaust air heaters for anti-icing, anti-frosting and heating of the accessory section of the engine, internal-combustion heaters for cabin and ground heating, and electric heating of remote accessories.

3.3 COMPARTMENT TYPE

3.31 *Non-military* compartment-type planes are invariably commercial transports. At present, the heating systems in these planes use either exhaust air heaters, internal-combustion heaters or exhaust steam heaters, with occasional installations of exhaust liquid heaters. Accessory heating is limited to heating of the pitot static head of the air-speed indicator, which is done electrically, and carburetor heating, which is accomplished by blowing air past the exhaust pipe and over the carburetor. Water heating is effected either by electric immersion heaters or, in planes with steam or liquid heaters, coils carrying steam or hot glycol. Often, hot water is stored in thermos bottles in order to avoid the need for heating it on the plane. This applies also to food, which is brought aboard hot and stored in heat-insulated containers.

Galley requirements on trans-oceanic airliners are met either by the use of electric hot plates, or coils containing steam or hot glycol.

Ice removal is accomplished entirely by means of rubber-boot de-icers on the leading edges of the wings and control surfaces, and, for the propellers, by means of anti-icer fluid which is sprayed over their blades.

From all indications it appears that this picture will change considerably after the war. Commercial travel at high altitudes and over long distances will require a much more complex heating installation. Anti-icing will take the place of de-icing. Instruments, battery boxes and gyro will have to be heated. Windshields and windows will require heat for anti-frosting. Adding these heat requirements to those of cabin heating, it is obvious that the old methods of heat supply do not suffice.

It is generally conceded that the task of heating will be split between two groups of heating systems: exhaust air heaters on at least two of the engines, and a system of electric heaters. The former will supply heat for anti-icing, anti-frosting, heating of the engine accessories and cabin heating. The latter will take care of heating of exposed and remote accessories.

The further development of exhaust air heaters and the ease with which ducts can be installed into a commercial plane—considered during the *design* stage—may eliminate the need for providing an internal-combustion heater for the heating of the empennage section.

Ground heating for land-based airliners appears to be unnecessary in view of the ground-heating equipment with which all regular landing fields are equipped. However, heating of flying boats by means of such equipment may not always be feasible. In such cases, the boat should be equipped with an integral ground heater of the internal-combustion type. During flight this heater can be used to supplement the exhaust air heaters.

3.32 *Military.* The selection of heat supply for military planes of the compartment type is based on essentially the same considerations as those for non-military planes. Spot and central internal-combustion heaters are preferably augmented by exhaust air heaters for anti-icing and similar tasks.

Electric heating is used even more extensively than on cabin-type planes since more current can be expended for such purposes.

Ground heating requires the installation of an internal-combustion heater which, during flight, may be used for the heating of the empennage section.

The heating of large, remote and inaccessible areas, such as gun turrets, the nose of the ship and unpressurized portions of a supercharged plane, is preferably accomplished by means of combustion spot heaters unless ducting of hot air to these parts is possible and practical.

Galley requirements should be met by the use of electric hot plates.

4.0 Specifications

After the heat supply has been calculated and selected, the designer must specify it in such a way as to make the results of his investigation, his conclusions and decisions available to those who are to design and furnish this equipment.

The sample calculations carried out in the previous chapters indicate the amount of data which must be supplied in order to design, for example, a suitable exhaust air heater. These calculations also illustrate the futility of stressing the need for lightness, ease of control, dependability, safety and other features which should be apparent.

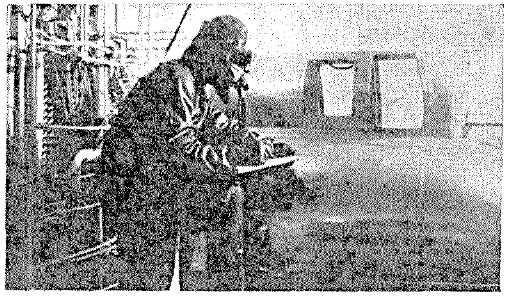

Fig. 112

Instead, it is more important to watch for four factors, inherent to military flying in particular, which are not always sufficiently considered in specifying aircraft heaters: (1) operation at low temperatures, (2) low air densities, (3) low humidities and (4) high gravitational forces.

In order to be sure that the vital and somewhat hazardous heating equipment will perform even under the most adverse conditions, and when it is needed most, a test program must be specified which is based on a combination of all conditions to be met.

Such requirements are not unreasonable since suitable test equipment for these purposes has been developed to a marked degree of perfection and permits the simulation of high-altitude conditions, taking into account all of the factors mentioned above. Figure 112 shows a test chamber, developed by the York Ice Machinery Corporation, which permits *test-flying* on the ground of an entire cockpit, including its accessories. Comparatively simple equipment suffices for endurance tests of individual components, such as shown in Fig. 113, which served to perform life tests on combustion chambers for Airmax Altiheaters.

A typical example of proper engineering is the heater relay shown in Fig. 114 which is manufactured by the G.-M. Laboratories. After thorough development to meet specifications, the final tests proved that this relay will operate successfully against a gravitational force of 15 g, at a temperature of −60° and air densities and humidities corresponding to 40,000 feet. Without such tests, there would be no assurance that the relay might not fail in a steep bank or dive at high altitude and make the entire heating scheme inoperative.

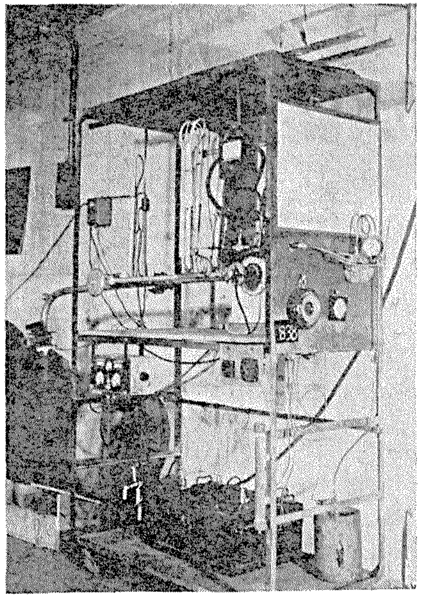

Fig. 113

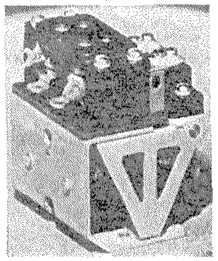

Fig. 114

For these reasons, the writing of sensible and intelligent specifications, and the proper choice of suppliers are just as important as correct calculations.

Once the heating equipment has met all tests and performed in accordance with specifications, there still remains the question as to whether the many assumptions on which the original calculations had to be based, are correct. However, only the steadily increasing data obtained through actual use can provide the designer with material to verify his assumptions and to replace them gradually with proven factors.

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XVIII

FUNDAMENTALS OF SOUNDPROOFING

1.0 INTRODUCTION

Soundproofing of airplane cabins has always been one of the major problems in the design of modern aircraft. It consists not merely of pasting some felt on the skin of the fuselage but requires observation of rigid rules with which everyone concerned with the design, maintenance and handling of airplanes should be thoroughly familiar. For this reason, a study of the fundamentals of soundproofing is of the greatest importance to all aeronautical personnel.

1.10 PHYSIOLOGICAL EFFECTS OF NOISE. Noise affects different people in different ways. Some persons seem to be, or easily become, immune to noise while others grow increasingly irritated and nervous if exposed to even little noise. Studies show that, as a whole, the noise encountered in factories and the streets of large cities has a progressively deleterious effect on the nervous system of the average person although this effect may not always be realized immediately.

The noise level in a non-insulated airplane cabin is far above the normal level of human endurance. This is illustrated in Fig. 115 which shows noise conditions in a number of places and vehicles, ranging from broadcasting studios to the cabins of four-engine bombers. The intensities are compared in three different ways, (1) by the noise *level in decibels*, which will be explained later, (2) the *Comfort Level* and (3) the *Speech Level.*

The comfort level is denoted as CL-, followed by a number which designates the degree of comfort or discomfort as shown in the table below:

Comfort Level: CL-1 .... Very comfortable;
CL-2 .... Comfortable;
CL-3 .... Slightly uncomfortable;
CL-4 .... Uncomfortable;
CL-5 .... Very uncomfortable;
CL-6 .... Painful.

Similarly, the speech level is denoted as SL-, followed by a number which designates the effort required for conversation as shown below:

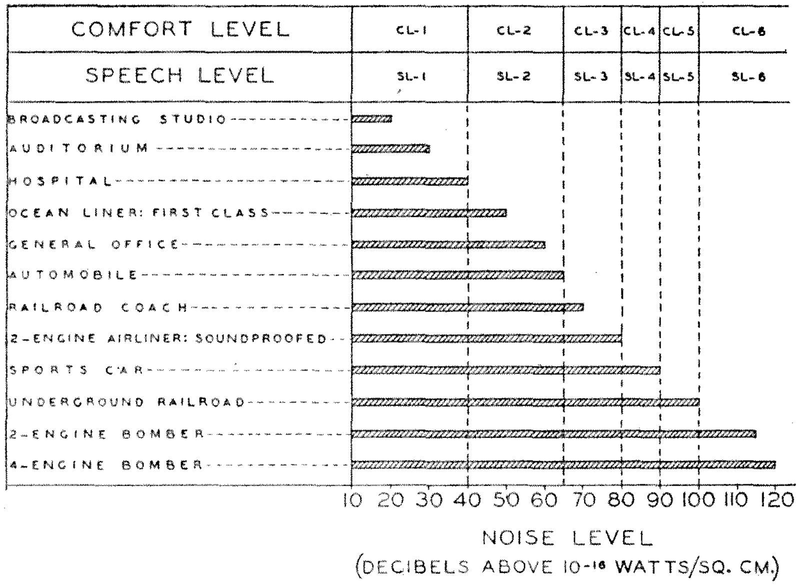

Fig. 115

Speech Level:	SL-1	Whisper;
	SL-2	Normal;
	SL-3	Raised voice;
	SL-4	Very difficult;
	SL-5	Shouting;
	SL-6	Impossible.

The values in Fig. 115 are somewhat arbitrary as available data vary widely and the results obtained by measurements depend on a great number of factors which can differ considerably, even for the same place. It is obvious, however, that the noise level on a non-insulated, multi-engine airplane such as a medium or long-range bomber, is very much above the limit beyond which noise becomes painful and regular conversation impossible.

Under these circumstances, it is not surprising that passengers on commercial airliners demand soundproofing as one of the main pre-requisites of comfort, and it will be remembered that Zand's investigations proved noise to be the number one discomfort on the early transports.[1] Therefore, soundproofing of the cabins of airliners is a commercial necessity.

What about military airplanes? Young and healthy persons are less affected than older ones. Thus, it should be expected that aviators

who are selected for their physical fitness are little if at all susceptible to the effects of noise, and that no costly weight need be sacrificed on military aircraft for soundproofing installations. This is true only to a certain degree.

In discussing the military value of various comforts (see Chapter II), it was stated that pilots have been found to suffer definite hearing losses, if exposed to very loud engine and airborne noises on aircraft for any length of time. C. C. Bunch[2] explains that hearing losses begin with tones of higher frequencies, or above 2000 cycles per second. With continued exposure, such as that experienced on long bombing missions, acuity for tones of lower pitch is lowered also and, since normal speech contains frequencies from 120 to 8000 cycles, it becomes increasingly difficult to understand certain letters or even words over the radio. The radio guide beam must be turned on louder than normal, and conversation over the intercommunication system is badly affected. Obviously, hearing thus impaired is a grave handicap when receiving instructions for maneuvers, landing or action.

The after-effects are equally disturbing. Flight crews report that, after lengthy trips, the sudden cessation of noise to which they had become accustomed—which may be termed *negative noise*—is as painful as the *positive noise* and that, for hours after de-planing, they find it difficult not only to hear but also to quiet their nerves.

Since even in military fliers a normal degree of sensitivity to excessive noise must be taken into account, a reasonable amount of soundproofing should be considered as one of the most essential comfort items on military aircraft.

1.20 *Theory of Sound.* Many engineers consider sound a rather abstract science. This may be due to the fact that very few of the analogies which connect other fields of physics can be applied to sound. As was stated in the case of heat transfer, most practically minded persons have neither the time nor inclination to bother about things which are too theoretical and complex to be of direct value to their work. However, just as the physician must be thoroughly familiar with the theory of a disease in order to be able to cure or fight it, is is essential to know the laws and phenomena pertaining to a physical effect before it is possible to utilize or counteract it. Thus, at least a limited knowledge of the theory of sound is mandatory for the practical understanding and use of soundproofing.

It is, of course, impossible in this book, to discuss sound and noise in more than a very general way. Those who wish to study this interesting science will find references to some excellent text books on this subject at the end of the chapter.

1.21 *Definition* of sound, as proposed by the Acoustical Society of America and approved by the American Standards Association, states that:

1. Sound is an alteration in pressure, particle displacement or particle velocity, propagated in an elastic material or the superposition of such propagated alterations.
2. Sound is also the sensation produced through the ear by the alterations described above.

Sound, as we hear it, is usually generated by vibration of a body and transmitted to the human ear by rapid contractions and expansions (condensations and rarefactions) of the transmitting medium, normally air. These contractions and expansions are registered by the brain as sound, if they occur at frequencies between 20 and 20,000 complete vibrations or cycles per second. The upper limit varies for different persons and with age, decreasing as the age increases. If the amplitude of the sound wave is very large or the sound disharmonious, the sensation is unpleasant and commonly termed *noise.* The measure of unpleasantness varies with the individual.

1.22 *Properties.* The velocity of a sound wave in air, at standard atmospheric conditions and at 68° Fahrenheit, is 1125 feet per second. It varies with the density of the air, that is, at different temperatures, atmospheric pressures and altitudes. It also increases slightly for very intense sounds.

The velocity remains practically constant at all audible frequencies but is somewhat greater at supersonic frequencies or those in excess of 20,000 cycles per second. The greater the frequency, the higher is the *pitch* of the sound.

Since sound travels in a longitudinal wave in which the vibrating particles move forward and backward in the direction of the wave, its properties are quite different from those of disturbances moving in transverse motion, such as radio and light waves. Most of these properties, at least as far as they concern soundproofing, relate to the intensity of sound. Therefore, it is necessary to discuss the measurement of sound before going any further.

2.0 MEASUREMENT OF SOUND

Foremost of all factors which aggravate the understanding of the phenomena of sound and noise, is the apparent complexity of their units. Unfortunately, sounds cannot be measured in units as simple as inches or volts or minutes. There are a number of reasons for this. Firstly, the ear does not add sounds arithmetically. In other words, if a sound is added to another one of the same intensity, the ear does

not add the two sounds to establish one of double intensity but rather to one of slightly higher intensity than that of the single sound. Secondly, two sounds of the same intensity but of different frequency do not seem equally loud to the ear. Thirdly, the intensity of a very loud sound may be as much as 2.5×10^{13} greater than that of a sound which can barely be heard. With such a tremendous range, an arithmetical method of measurement, that is, addition or multiplication of a normal unit, would be very impractical.

The case would be hopeless, if it were not for a very handy, although often disliked tool which mathematics provides, namely the logarithmic scale.

2.1 THE DECIBEL. It all started when telephone engineers sought to define the relationship of electric power ratio to sound sensation.[3] As sound is converted into electric energy and travels through many miles of telephone wire, an *attenuation* or decrease in energy takes place due to line losses which must be measurable by some sort of unit so that they can be compensated for accurately.

The first unit used was the so-called *loop mile.* This unit was equal to the loss in one mile of standard telephone wire of given properties and would have been acceptable were it not for the fact that attenuation varies with frequency. The next step was to give the line loss in terms of a ratio, namely that of the power input to the power output. Since the range between input and output is very large and increase or decrease is not arithmetical, a unit was evolved which shows the power loss in terms of the logarithm of the ratio between power output and input. This unit was called the *Bel* in honor of the inventor of the telephone, Alexander Graham Bell, and is expressed by the following formula:

$$\text{Power Loss in Bels} = \log \frac{\text{Power Input}}{\text{Power Output}}$$

Similarly, the difference in the intensities of two sounds, I_1 and I_2, is given by:

$$\text{Bel} = \log \frac{I_1}{I_2} \tag{2}$$

Since the Bel is somewhat larger than convenient in acoustics, it was finally decided to introduce a unit which is one tenth of a Bel and which was, therefore, called the *decibel,* or abbreviated, *db.* Thus, the formula finally adopted to express the difference between two sound intensities is:

$$\text{db} = 10 \log \frac{I_1}{I_2} \qquad (3)$$

All of this sounds rather complicated but it is not necessary to understand the derivation of formula (3) fully as long as it is used intelligently. It is the fundamental equation for all calculations pertaining to sound, and a brief analysis of its nature might be helpful in making it a little easier to work with.

2.2 SOUND INTENSITY. It must be remembered always that the decibel is not a unit in the common sense of the word but a ratio or, rather, the logarithm of a ratio. The logarithm or *log*, incidentally, is the Briggs logarithm, often denoted as log_{10}. It should be borne in mind further that the logarithm of the ratio of two numbers is equal to the difference between the logarithms of these numbers. For instance, the log of 1,000,000 divided by 100 equals the log of 1,000,000 minus the log of 100 or:

$$\log \frac{1,000,000}{100} = \log 1,000,000 - \log 100.$$

Since the log of 1,000,000 is 6 and that of 100 equals 2, the term

$$\log \frac{1,000,000}{100} = 4.$$

Assuming now that an electric signal of 100 microwatts is fed into a radio amplifier and the output has been measured to be 1,000,000 microwatts or one watt, the gain of this amplifier in db would be:

$$\text{Gain} = 10 \log \frac{1,000,000}{100} = 10 \times 4 = 40 \text{ db}$$

or, in other words, the difference between the output and input levels is 40 decibels.

If the fundamentals of calculation by means of the logarithm are known, it is now easy to see why a large difference between two sound intensities gives a comparatively small figure for their difference in terms of decibels, and that the absolute value of the intensities is unimportant since only their ratio is considered. Thus, if the intensity of one particular sound, I_1, is ten times greater than the intensity of another sound, I_2, they differ by ten decibels because:

$$\text{db} = 10 \log \frac{I_1}{I_2} = 10 \log \frac{10}{1}$$

The logarithm of 10 equals 1, so that:

$$\text{db} = 10 \times 1 = 10$$

If two intensities differ by one decibel, the log of their ratio must be 1/10. The number whose logarithm equals 1/10 is 1.26, and the intensity of a sound must be increased by 26% in order to raise its noise level by 1 db.

It is interesting to see what happens, if the intensity of a noise is doubled. Assume that the noise produced by an airplane engine has been found to measure 100 db. Now another engine is started, also producing a noise of 100 db. In adding these two noises, the first thought would be to add 100 and 100 and call the total din 200 db. However, a now simple calculation shows an entirely different and quite surprising result. I_1 is twice as large as I_2 because the original intensity I_2 has been doubled. Therefore;

$$\text{db} = 10 \log \frac{1 + 1}{1} = 10 \log 2$$

Examination of the log tables shows that the log of 2 is approximately 0.3 so that:

$$\text{db} = 10 \times 0.3 = 3$$

Consequently, adding the noise of one airplane engine which produces 100 db to another one making a noise of the same intensity, raises the noise level by only 3 db. Since it does not make any difference whether the two sources of noise produce 100 or 50 db, as long as the final noise intensity is twice as large as the original one, it follows that doubling the physical intensity of a noise, no matter how small or large, results in an increase of 3 db. Conversely, cutting the intensity in half, reduces the noise level by only 3 db.

Although the question of existing and desirable noise levels on aircraft has not yet been discussed, it becomes apparent now that noise reduction is not an easy task, if even elimination of one of the two engines on an airplane results in such a small decrease in noise level. To understand this phenomenon better, it is necessary to find out how the human ear reacts to all of this theoretical diagnosis of its wants.

2.3 REACTION OF THE EAR. It had been mentioned before that the range between the faintest sound which the average human ear can hear and the loudest sound which it can register without injury is extremely large. This is possible only because the ear does not add intensities arithmetically but logarithmically. Thus, instead of adding intensities, it adds decibels.

It so happens that, if an average person can just about detect the difference between the intensities of two sounds, these sounds differ by one decibel, or, physiologically, the decibel is the minimum difference in level which the human ear can register. The fact that the physical and physiological units are very similar is not purely coincidental. However, their real relationship has not yet been fully understood and is still the subject of research.

It is quite fortunate that nature has made the human ear hear logarithmically. If, for instance, a musical instrument which produces a sound of 50 db is augmented by another one, also producing 50 db, the total noise level is not 100 db but, as will be remembered, increases by only 3 db so that the new noise level is now 53 db. Adding a third instrument, which produces 53 db, again doubles the sound intensity but raises the total noise level only to 56 db. Since levels above 100 db are registered as painfully loud, it would be impossible to listen to an orchestra, if the sounds of dozens of instruments would add arithmetically. Actually, the combined level of 56 db which results from the playing of the above mentioned three instruments causes the sensation of very soft music.

This reaction of the ear is not easy to understand, and the statement that the difference between the noise made by one airplane engine and that made by two engines is only 3 db or merely three times the minimum difference the ear can barely detect, meets, at first, with considerable skepticism. However, the point is proven, if one stands close to a two-engine airliner which is about ready to take off. As the first engine is started, it produces a roar and din which is so loud that it is painful to the ears. After a few seconds, the second engine is started, and it will be noticed that the combined noise from the two engines is not very much louder than that caused by a single one. The whole difference is only 3 db.

By the same token, as the airliner comes to a landing, the noise from its engines is highly uncomfortable although they are merely idling. When the first engine is stopped the noise seems hardly reduced and is still very uncomfortable.

A classic example of this phenomenon is that of an applauding audience. Assume that there are 100 people in an auditorium who applaud with the same degree of intensity. Suddenly, half of these people stop applauding. Amazingly, there is not as much decrease in noise as one might expect—again only 3 db. However, if all 100 people, simultaneously, reduce the intensity of their applause, a very marked decrease in noise will be observed.

The lesson to be learned from these studies shows that it does little good to eliminate only one or another source of noise on an airplane, and that even removal of an entire engine or total soundproofing of all propellers contributes relatively little to the soundproofing scheme. Drastic reduction of the noise produced by every contributing source is the only efficient means for worthwhile reduction of the combined noise level as the ear hears it.

2.4 REFERENCE LEVEL. In the previous pages the term *noise level* has been used quite freely. It is evident that it refers to a noise of a certain db rating. Thus, a noise level of 80 db is understood to represent a total noise, produced by one or more sources which add up to 80 db.

However, if it is remembered that the decibel is not a unit like the inch or pound, but a ratio between two intensities, it will be found that the term "80 db" as such is meaningless in describing the intensity of a certain noise. It merely implies that the intensity of this noise is 80 db greater than that of another one, without giving the quantity of the latter. Looking at formula (3) again:

$$80 \text{ db} = 10 \log \frac{I_1}{I_x}$$

in which I_1 is the intensity of the noise which was said to amount to 80 db, and I_x is the intensity of an unknown noise to which I_1 must be compared according to the definition of the decibel. Conversely speaking, all that the term "80 db" conveys in describing the intensity of a noise is that it is so-and-so many times larger, but it does not say larger than what.

For this reason it is necessary to establish a definite value for I_x, and to have it understood that, in expressing noise in terms of db, the number of db of a noise always refers to the difference between this noise and the agreed-upon reference noise. Then, if a noise is merely given in db's, everybody knows that its intensity I_1 is a corresponding number of times greater than the reference intensity. This differs in no way from other units of measure because, in stating that a wire is 10 inches long, it is understood that the wire is ten times an agreed-upon unit of length which has been called *inch*. If the length of the wire were simply denoted by the figure ten, it could mean inches as well as feet or miles.

Therefore, in expressing a noise level in db, it is always necessary to refer to the level from which the noise is measured, or the so-called *reference level.*

A number of convenient reference levels have been recommended in the past of which three in particular have been used widely. The first one of these levels proposes the threshold of hearing as the zero mark from which all other levels are measured. The disadvantage of this scale is its dependence on the subjective reaction to auditory sensations which may vary widely for different individuals. More reliable is a mathematical definition such as by establishing a reference sound intensity. This method is used in the other two scales.

Sound intensity is measured in watts/sq cm, while sound pressure, which will be discussed shortly, is measured in conventional, small units of pressure, such as the dyne/sq cm or the *millibar* (1 mb = 0.0145 lb/sq in.). One threshold, which had been used quite widely up to a few years ago, is the sound intensity corresponding to a sound pressure of 1 millibar. On the basis of this scale, a noise level must be designated as "x db above 1 mb."

The American Standards Association has adopted a different level which is not only somewhat more convenient but quite close to the threshold of hearing. The zero point on this scale is a sound intensity of 10^{-16} watts/sq cm which, incidentally, corresponds to a sound pressure of 0.207 mb or 0.0002 dynes/sq cm. This intensity is slightly less than the threshold of audibility for the average ear at a frequency of 1000 cycles per second. Since noise levels vary not only with intensity but also with frequency, the correct way of identifying a noise level in this scale is to state that it is "x db above 10^{-16} watts/sq cm at 1000 cycles/second."

In order to convert decibels above one millibar into decibels above 10^{-16} watts/sq cm it is only necessary to add 14 db to the millibar scale. These complications and subsequent errors could be avoided, if there were general agreement on the scale. Since it appears that the one adopted by the ASA is finding increasing acceptance, all noise levels mentioned hereafter shall be understood to be based on a reference level of 10^{-16} watts/sq cm, at a frequency of 1000 cycles/sec.

2.5 SOUND-MEASURING METHODS. There are two ways of measuring sound: the *subjective* and *objective* methods. In the former, the sound to be measured is compared with one of known intensity. As this method depends on the individual reaction which is different for every person, it is not very reliable nor accurate although it is quite simple. More common and useful is the objective method which employs a so-called sound-level meter. This instrument consists of a microphone and a high-gain audio amplifier, with a milliameter across its output which is calibrated in decibels. Since engineers are more interested in the relative loudness of a sound as it is perceived by the ear rather than its physical intensity, the instrument contains a weighing network so that its sensitivity can be decreased for those frequencies to which the ear is less sensitive. This arrangement has the further advantage that it can be used to determine which frequencies predominate in a given noise and to what extent.

Measurement of sound by mechanical means and without the aid of amplification is not impossible but highly impractical. The energy contained in a sound loud enough to produce an auditory sensation is extremely small, although it might appear that the noise from an airplane engine, for instance, might have a good deal of mechanical energy. However, measurements have shown that the average power of a speaker is only between 25 and 50 microwatts. Consequently, it would take 15 million people speaking simultaneously to produce the equivalent of one horsepower.[4]

2.6 LOUDNESS. To complete the picture, it is necessary to mention briefly two other concepts in connection with sound, not only on account of their importance but because they often result in misunderstandings.

The first concept is *loudness.* Loudness and intensity are by no means the same. The former is a physiological quantity while the latter is a purely physical one. The ear judges a sound not only by its intensity but also by its frequency. Thus, two sounds of the same intensity and frequency are perceived as equally loud. However, two sounds of different frequency are adjudged as being of different loudness although their intensity is the same. This difference can be very large. For instance, a 90-cycle note at 40 db seems to sound equally loud as a 400-cycle note at 10 db. For this reason, it has been necessary to agree on a reference frequency, namely 1000 cycles/sec, in establishing a reference level for loudness.

Accordingly, the intensity of a sound refers to the energy contained in this sound, without considering the sensation which it will create in the ear. The loudness level of a sound, on the other hand, is said to be equal to the intensity level in decibels of a 1000-cycle note which sounds equally loud.

The unit of loudness is the *phon.* By definition, zero phons equal zero decibels at 1000 cycles. Similarly, 10 phons equal 10 decibels, if these ten decibels refer to the intensity of a 1000-cycle note. Phons will not be used in this text and have been mentioned merely to emphasize the difference between intensity and loudness.

2.7 SOUND PRESSURE is another concept requiring a few explanatory remarks. If a sound wave strikes an object, such as the ear drums or any other medium in its path, it exerts a certain pressure which is termed *sound pressure.* Sound intensity is related to sound pressure by the following equation:

$$I = \frac{p^2}{d \times c} \tag{4}$$

in which

I = sound intensity in ergs/sec/sq cm
p = effective sound pressure in dynes/sq cm
d = air density in grams per cc
c = sound velocity in cm/sec

The value for $d \times c$, under average conditions, is about 41. Substituting for intensity in equation (3),

$$\text{db} = 10 \log \frac{P^2}{P_0^2}$$

From this is derived:

$$\text{db} = 20 \log \frac{P}{P_0} \qquad (5)$$

This formula expresses the decibel in terms of sound pressures instead of intensities. As mentioned before, the sound pressure at the threshold of hearing equals 0.0002 dynes/sq cm, which again corresponds to the reference intensity of 10^{-16} watts/sq cm at 1000 cycles.

It should be noted that the log of the ratio of two sound *pressures* must be multiplied by 20 in order to equal the number of decibels by which these two pressures differ while the log of the ratio of two sound *intensities* is multiplied by 10 to give the number of decibels by which the two intensities differ. As was shown before, doubling the intensity of a sound, increases the noise level by 3 db, but, doubling the sound pressure results in an increase of 6 db.

Inasmuch as the reference level used in this text is based on a reference intensity, the concept of sound pressure has been discussed only for the sake of avoiding misunderstandings.

3.0 Principles of Soundproofing

The foregoing explanations cover but a small fraction of the many and complex phenomena of sound. However, if they are fully understood, they will provide the fundamental knowledge required for the reduction of noise in airplane cabins.

In applying this knowledge, two factors stand out, namely, that noise reduction must be obtained by simultaneous reduction of the noises produced by all of the contributing sources rather than total elimination of the one or another source and, second, that there must be a considerable reduction in noise intensity to bring about an appreciable decrease in noise level as the ear perceives it.

There are three basic methods of soundproofing:

a. Reduction of noise at its source by minimizing or eliminating the factors responsible for the noise. This method is termed *primary soundproofing*. A typical example is the replacement of a noisy bearing in an electric motor by a silent one.

b. Reduction of noise by impeding its transmission and facilitating its absorption. This method is termed *secondary soundproofing*. Conventional soundproofing installations in homes and offices are a good illustration of this method.

c. Reduction of noise by a combination of methods (a) and (b). Examples of such a combination are the soundproofing installations in the cabins of modern airliners.

3.1 PRIMARY SOUNDPROOFING. Reduction of noise at its source is usually more difficult to accomplish than secondary soundproofing. While the latter is being undertaken in conformance with definite rules, the former depends on factors which are different in every case. Furthermore, if it is desired to reduce the noise created by a particular piece of machinery, it is necessary to be familiar not only with the requirements of soundproofing but also be an expert in the design or re-design of such a machine. In addition, the changes required for noise reduction must not change the operation of the machine nor, in many instances, its appearance, price, weight or size.

Sometimes, primary soundproofing can be achieved by very simple means, such as tightening of rattling parts, strengthening of vibrating components, replacement of loose or faulty members, insertion of shock absorbers, elimination of sharp edges on rotating devices and other common tricks. Whenever there is a source of vibration or a prime mover, other parts may be made to vibrate and become prime movers themselves, for a number of reasons. The study of these reasons is the prerequisite of efficient, primary soundproofing.

Often, reduction of the noise at its source is impossible. For instance, an office may be located above a very noisy factory or near a busy thoroughfare. In such cases, the desire or need for more comfortable noise levels must be met by the second phase of soundproofing.

3.20 SECONDARY SOUNDPROOFING is designed to attenuate or decrease the intensity of an existing noise to such an extent that the new level is as far within the limits of comfort as is possible and practical. This can be achieved either by impeding the transmission of the sound wave into the soundproofed room or by its absorption within the room.

3.21 *Sound Transmission.* The most common medium for the transmission of sound is air. Water is another medium which transmits sound very well. This is utilized, for instance, in *sounding* ocean depths by sending a sound to the bottom of the ocean and measuring the time it takes the reflected sound to return to the ship. Steel, too, transmits sound which can be demonstrated by pressing the ear to a railroad track and hearing the rumble of an approaching train although it may not yet be visible to the eye.

Different materials transmit sound to a different degree. The fraction of sound energy which is transmitted per unit area of a material is called the sound transmissivity of the material and denoted by the letter t. Transmissivity times the total area is called the *transmittance* of the room and designated by T. The transmittance of a room is the ratio of the sound energy within the room to that existing outside of its walls. The decrease in sound energy is called the transmission loss and measured in decibels.

The phenomenon of sound transmission through a wall is explained by the fact that a sound wave, upon striking a body in its path, makes it vibrate and this body itself becomes a source of noise. If the wall or partition is rigid, its transmissivity depends primarily on its mass and is approximately proportional to the log of the mass per unit area. Thus, the heavy masonry in well-built houses attenuates noise so much that the sound energy transmitted through the walls is negligible.

Obviously, such a scheme is not possible on an airplane. As the insulating value of a wall increases so slowly with increasing mass, unreasonably large weights would be necessary in order to obtain appreciable results. Zand[1] states that it would take a weight of 161 lb/sq ft to obtain fair comfort in an airplane cabin by relying entirely on transmission loss.

The walls, floors and ceilings of an airplane cabin are of rather thin material so that they vibrate easily. Since the mass per unit area is small, the degree of vibration now depends mainly on the stiffness and damping coefficient of the wall. Consequently, a maximum transmission loss through the walls of the cabin is obtained by so designing them as to minimize the tendency for vibration and by applying efficient damping materials.

Apart from the difficulties in reducing transmission, there is another one of those peculiar properties of sound which aggravates the soundproofing scheme, namely the ability of sound waves to squeeze through the smallest opening. It shall be assumed that the noise outside of an airplane cabin is 100 db. If the entrance door is fully open, the noise inside the cabin will likewise have a level of 100 db. As the door is being closed, the inside noise by no means decreases in proportion to the decrease in the opening which admits the noise. Even closing the door down to a crack 0.01 inch wide reduces the noise level only by 10 db. It is necessary to shut the door absolutely tight to obtain a sizeable reduction in noise.

From this follows that even the smallest openings should be avoided.

On the other hand, there are openings for ventilation and other purposes which are unavoidable. On military airplanes, numerous openings are required for the disposition of equipment such as guns. Therefore, the outside noise will squeeze through whatever openings it finds and gradually build up the noise level inside until equilibrium is reached with that existing outside.

This phenomenon can be compared to a leak in the bottom of an otherwise watertight partition inside of a tub, with water on one side of the partition and air on the other. If the level of the water is kept constant by replacing whatever is lost by leakage, water will flow through the leak into the empty side of the tub until it has reached the same level on the formerly empty side as exists on the other side of the partition. Unless the leak can be completely plugged, there is only one way of keeping the water level in the second compartment from building up, and that is by draining the water out as fast as it leaks in.

In soundproofing, the noise which leaks into the cabin in spite of all precautionary measures can be disposed of by absorbing it. Therefore, sound absorption is the second and most important tool of secondary soundproofing.

3.22 *Sound Absorption* has a twofold purpose, namely, to eliminate or at least minimize noise which is either transmitted into or created inside of the cabin. This can be accomplished by the use of materials which absorb or soak up the noise.

Porous and fibrous materials attenuate noise by viscous and frictional losses within the capillary pores so that the sound energy is converted into heat. The logarithm of the energy reduction in db is roughly proportional to the thickness of the material.

The absorbing capacity differs for various materials and is expressed by the absorption coefficient c. This coefficient represents the percentage of noise absorbed as compared to that absorbed by an open window of the same area. This definition may sound a little odd inasmuch as an open window could not very well be said to absorb sound. However, the engineer is mainly interested in finding out how much of the sound energy is being reflected back into the room. The difference between the sound energy of a sound wave striking a wall and that contained in the reflected wave represents the amount which has been absorbed by the wall. Since an open window does not reflect any portion of a sound wave passing through it, its absorption coefficient is said to be 1.0. Consequently, if the coefficient of a felt is given as 0.7, one square foot of this material is equivalent to 0.7 square foot of open window area in its ability to quench reflection.

The absorption coefficient of a material varies with frequency. Thus it is necessary either to agree on a reference frequency—usually 512 cycles/sec—or provide the coefficients for several basic frequencies. (See next chapter.) The latter is preferable because a soundproofing installation may have to be designed for maximum absorption at frequencies other than 512 cycles/sec.

The total absorption, C, of a room consists of the sum of all areas times their individual absorption coefficients. Therefore:

$$C = c_1 \times A_1 + c_2 \times A_2 + c_3 \times A_3 + \cdots \qquad (6)$$

The unit of C, the absorption or absorbing power, is the *sabine*, so-called for a famous scientist of that name. Thus, a room is said to have a certain number of sabines of absorbing power. This includes not only the sum of all areas times their absorption coefficients but also other objects which tend to absorb sound energy. For instance, the absorbing power of a seated person is about 3 sabines, that of the conventional airplane seat approximately 2.8 sabines while other objects in the cabin, such as curtains, parcels, etc., may add from 10 to 20 more sabines. Absorption coefficients of various soundproofing materials used for aircraft are given later in the text. An approximate formula for calculating the absorbing power of a room without occupants, carpets, drapes or similar furnishings is given by Kunen[5] as:

$$C = 0.3V^{2/3} \qquad (7)$$

in which C is the absorbing power of the empty room in sabines and V the cubical content of the room in cu ft.

3.23 *Application of Secondary Soundproofing.* Having learned about transmission and absorption of sound, it is now possible to apply this knowledge to the design of a soundproofing installation. To do so, it is merely necessary to remember the equation which establishes the relationship between noise reduction on one side, and transmission and absorption on the other.

If C denotes the sum of all areas times their individual absorption coefficients or the total absorption of the cabin in sabines, and T represents the sum of all areas times their individual transmissivity or the total transmittance, then the noise reduction is:

$$\text{db} = 10 \log \frac{C}{T} \qquad (8)$$

This formula can be used either to find the noise reduction obtained by a particular installation or, if the noise reduction is specified and the transmittance established, the amount of absorption which must be provided.

The noise reductions which can be obtained for different values of the absorption coefficient c and the transmissivity t, are shown graphically in Fig. 116. Using an example by D. C. Greenwood[6] who provided these curves, it shall be assumed that c has been found to measure 0.1 and t to equal 0.01. Then the noise reduction is 10.4 decibels. Now, if it is desired to obtain a further reduction of, say, 10 db, it is necessary either to decrease t by changing the structure of the cabin or increase c

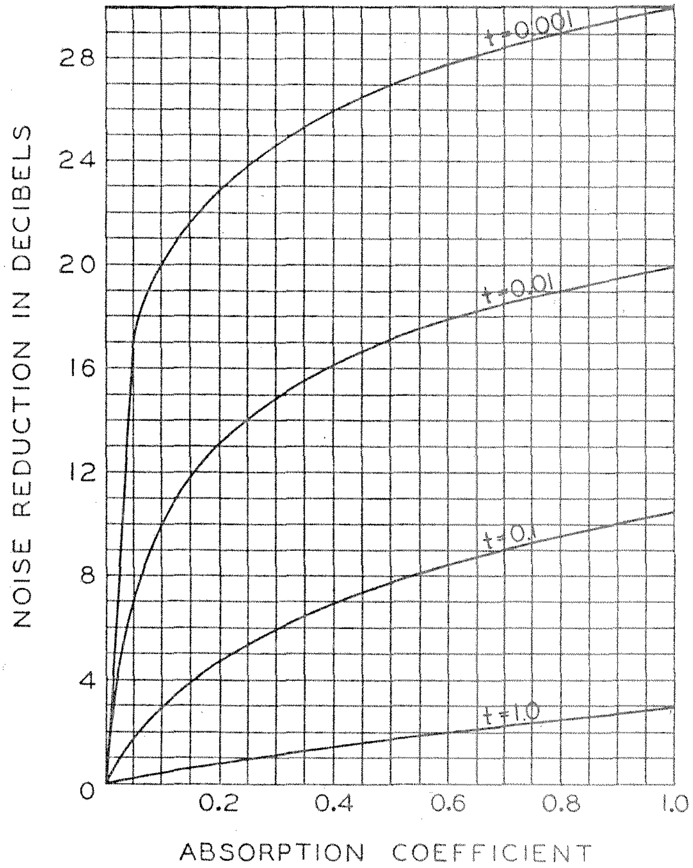

Fig. 116

by means of a more complex soundproofing installation. The choice between these two methods or a combination hinges mainly on considerations of weight although inability to change the cabin structure may leave no other alternative than to sacrifice weight in order to obtain the required reduction.

There are a few factors which make these calculations somewhat more complicated than they might now appear to be. First of all, it *is* very difficult and, often, impossible, to calculate the total noise, generated both inside and outside, with a reasonable degree of accuracy. This applies equally to the total transmittance of the cabin. Furthermore, it is not easy to foretell what frequencies will predominate in particular sections of the fuselage. Finally, conditions during flight and on the ground are quite different.

For this reason it is usually simpler, quicker and more accurate to establish all doubtful factors during a test flight in the plane before it is soundproofed. Such a flight shows immediately the main sources of noise, as well as the levels and frequencies of such noise. From the data thus obtained it is possible to calculate and design both primary and secondary soundproofing. This procedure is the most economical since it is based not on assumptions but on true values, and thus helps to prevent costly errors.

It is very probable that, in the course of time, there will be a sufficient collection of empirical values and experiences to anticipate accurately the soundproofing requirements of an airplane while it is still in the design stage. At the present time, very few of such data are known and those not general enough to apply to more than a few specific and related cases. An example of such a calculation is carried out in the next chapter.

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XIX

SOUNDPROOFING OF AIRCRAFT

1.0 INTRODUCTION

As a rule, the noise produced by a vehicle in motion is the higher, the greater its speed. For instance, an ordinary sailboat cruising leisurely at 4 mph makes a total "noise" of about 45 db while a twin-engine bomber, travelling at 250 mph, produces approximately 100 million times that much.

As the airplane moves at a speed very much higher than that of any vehicle on the ground, with the principal sources of noise closer to the occupied spaces than in any other conveyance and greater restrictions as to weight than exist anywhere else, it presents unique problems of soundproofing which are quite different from the problems known heretofore.

If it is desired to reduce the noise in the average airplane cabin to a level of reasonable comfort, it is necessary to bring about a reduction of from 30 to 40 decibels. As was shown in the previous pages, so large a reduction is extremely difficult to achieve. With only small areas available for treatment and the weight allotments very low, the absorbing power of an airplane cabin is as limited as is the capacity of a sponge to soak up water. Therefore, only a perfect combination of all phases of both primary and secondary soundproofing can result in an installation which meets all of the many requirements.

2.0 PRIMARY SOUNDPROOFING

Primary soundproofing has as its purpose the attack on noise at its source or sources. In order to reduce the total noise level thereby, it is necessary to reduce the noise level of every contributor to the greatest possible degree without affecting the performance, operation and other characteristics of the airplane. The first step in this direction is an analysis of the noise existing on an aircraft by studying its sources.

2.1 SOURCES OF NOISE ON AIRPLANES. The noise in an airplane cabin, as perceived by its occupants, is a composite of noises of different intensities and frequencies which are contributed by a variety of sources. Although investigators differ as to the order of magnitude in which the noises produced by these sources should be listed as well as to their relative levels, it is generally agreed that the noise caused by the propellers is the main contributor. According to data provided by Zand,[1] the exhaust noise and the noise created by the ventilating system come next. Airborne noises, engine clatter and aerodynamic noises, in this order, conclude the list. This results in the following tabulation which is quite representative although it may change somewhat from one installation to the other:

Propeller	122 db
Exhaust	118 db
Ventilating Noise	114 db
Airborne Noises	108 db
Engine Noise	104 db
Aerodynamic Noises	94 db
Total Noise	124.3 db

The decibels contributed by each source, as shown above, represent average noise levels for inefficient design. By logarithmic addition, the resulting total noise is found to be 124.3 db which is so far above the level of comfort, that secondary soundproofing alone could not possibly reduce it enough. For this reason, primary soundproofing must contribute a reduction of at least 20 db which is quite possible as will be shown in the following.

2.2 PROPELLER NOISE consists of two components, namely the rotation noise and the vortex noise. The former is produced by the rotation of the propeller and has a frequency equal to the number of rotations per second, times the number of blades. The vortex noise is caused by the circulatory and whirling airflow around the wing tips and directly proportional to the tip speed. According to several authorities,[1] the noise level created by a 3-blade, metal propeller can be calculated approximately by the following equation:

$$\text{Noise level (db)} = 19 + 0.11\,V \qquad (1)$$

in which V is the tip speed in feet/sec.

As the tip speed approaches that of sound, the noise becomes unbearably loud and painful to the ears. Apart from the fact that such extreme noise facilitates detection of military airplanes by the enemy's sound detectors, it is an indication of drastic reduction in propeller efficiency due to compressibility effects.[2] Thus, there is a triple reason for reducing the tip speed.

The noise of a propeller has unusual directional characteristics. The zone of very loud noise extends roughly from 3 feet forward to 5 feet aft of the propeller plane or disk, and is the loudest in the plane itself. If the clearance between the propeller tip and the fuselage is too small, violent panel vibration might result which causes not only a considerable increase in noise but also crystallization of the metal. Zand describes one case in which the clearance between the propeller tip and the fuselage was only 2 inches. As a consequence, the panel under the propeller vibrated with an amplitude of over ¼ inch, creating an exceedingly loud noise. This condition was relieved by inserting a *floating* panel and taking the stresses up by two diagonal wires. Now the panel vibrated noiselessly, and the noise level was reduced by 10 db which would have been extremely difficult to accomplish any other way.[1]

On the basis of these experiences, the following rules can be established for reduction of noise caused, directly or indirectly, by the propeller:

1. Keep the tip speed down to a minimum and let it never exceed 800 ft/sec at cruising speed;
2. Keep the clearance between propeller tip and fuselage to at least 12 in. and, if at all possible, more;
3. Do not place any part of the cabin in the plane of the propeller;
4. Avoid placing other than baggage and similar utility compartments in the maximum noise zone, that is, within 5 ft aft or 3 ft forward of the propeller plane;
5. Provide rigid sections with deadened panels within the noise zone. Do not use curvatures of more than 50 in. radius. If this cannot be avoided, stiffen area by stringers to minimize vibration;
6. Avoid placing windows or hatches in the noise zone; they do not permit application of secondary soundproofing.

Adherence to these simple rules may result in a noise reduction of from 18 to 22 db. A number of years ago, A. H. Davis[3] gave the following values and methods for reducing propeller noise:

10 db	per 100 ft/sec reduction in tip speed;
1 db	per degree in pitch setting;
10 db	for change to conventional thin section;
5 db	per foot diameter increase of propeller;
10 db	for change to four blades.

The last two changes are understood to apply for given power, speed and other operating characteristics.

2.3 EXHAUST NOISE. The intensity of the noise caused by the exhaust is exceeded only by that of the propeller. In many cases, the former is even larger than the latter. Reduction of the exhaust noise is, therefore, of prime importance.

There does not appear to be agreement on the usefulness of mufflers in the exhaust. The Piper Aircraft Corporation was the first to adapt a muffler to a light airplane and uses it now as standard equipment. Whether mufflers are to be recommended for engines of large power output, is questionable. From available data it seems that the gain in overall noise reduction is not commensurate with the increase of back-pressure in the exhaust nor the added weight.

One of the most effective means for decreasing exhaust noise is to place the point of exhaust as far away from the soundproofed portion of the ship as possible since sound intensity decreases approximately as the inverse square of the distance. Hence, exhaust pipes should be located on the outboard side of the nacelles, below the wing in a low-wing plane and above the wing in a high-wing plane. Care must be taken to avoid the possibility of exhaust gases striking any part of the fuselage as this will result in vibration of the affected panels.

Exhaust noise is very loud on engines with short exhaust stacks. Therefore, noise can be decreased considerably by properly designed collector rings and exhausts which not only permit the exhaust gases to cool to some extent before being ejected but also carry them further away from the fuselage, with nacelles or wings acting as baffles.[2]

A typical construction is illustrated by the Solar Aircraft manifold assembly, shown in Fig. 117. The dished outlet fits into a "socket and ball" joint which, among other advantages, impedes transmission of engine vibrations through the exhaust system. Figure 118 shows the components of an exhaust assembly, also manufactured by Solar Aircraft Company, which emphasizes the complexity required for good performance in all respects. Incidentally, the three holes seen in the section on top serve for the insertion of steam or glycol boilers which have been described in the chapter on heating systems.

Efficient design of the exhaust system may result in a noise reduction of from 14 to 18 db.

2.4 VENTILATING NOISE. In order to supply the air necessary for ventilation, an opening must be provided in a positive-pressure area of the airplane through which the required air quantities are scooped or taken in. As was shown before, every opening leading into the cabin will admit noise from the outside and thus contribute to raising the noise level within the cabin.

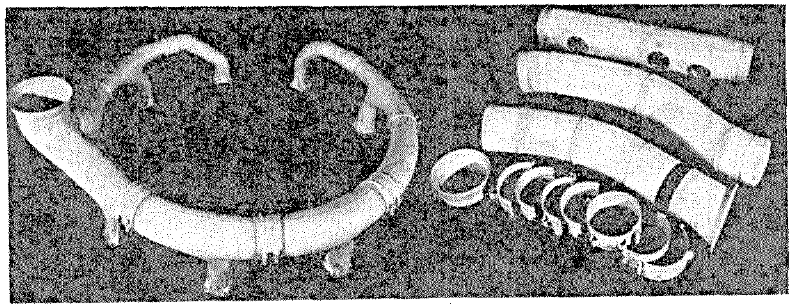

Fig. 117 *Fig. 118*

On the other hand, it was also shown that reduction in the size of an opening will not appreciably attenuate the noise admitted through it. Furthermore, a decrease in the ventilating opening would result not only in greater back pressures but also higher air speeds with accompanying increase in noise. For this reason, the intake opening should be left as large as indicated by the calculations discussed in previous chapters.

As long as there must be a sizeable opening to the cabin, the noise should be effectively reduced before it reaches the interior. This can be done in a number of ways.

The first rule is to place the air intake into an area of least noise, and to design the scoop to avoid "screaming" and "whistling." The second rule calls for the use of an acoustical capacity which tends to attentuate the noise. Such a capacity is a well-designed ducting system. The ducts should be lined with kapok protected by aluminum gauze or mesh. They must be held rigidly and provided with elastic connections to prevent the transmission of vibrations from one section to the next. If blowers are used, transmission of the blower noise through the duct system should be avoided. If need be, an acoustical filter should be employed.

Finally, the air velocity in cabin inlets and outlets should not exceed 1200 fpm. In nonsoundproofed portions of the fuselage this speed may be increased to about 3000 fpm. Observance of maximum permissible air speeds is particularly important since high air speeds result in a very large noise increase. Considerations of weight and space may make it desirable to decrease the size of the ducts which, in turn, would increase the velocity. In such cases it is necessary to arrive at a compromise by deciding between the relative importance of noise reduction on one hand and weight and space on the other hand.

The noise reduction which can be achieved by efficient design of the ventilating system is greater than that for any other source of noise and may amount to as much as from 38 to 42 db, thus reducing ventilating noises from the third largest to the smallest contributor. This proves that the requirements of soundproofing must be considered during every phase of designing the ventilating system, including the heating plant.

2.5 AIRBORNE NOISES are defined as such noises as originate within the cabin during flight. They may be caused either by inefficient design of the fuselage or by accessory equipment.

Because the structure of the airplane is exposed to constantly changing loads, forces and stresses during flight, it tends to vibrate readily. Therefore, any structural part within the cabin is apt to become a source of noise. For this reason, the fuselage should be so designed as to eliminate stressed members or webs within the cabin. Large, flat panels should be broken up into individual panels or provided with suitable stiffeners. In doing so, symmetrical surfaces such as parallel stiffeners should be avoided.

Bulkheads are a major problem because they contain not only large unsupported panels but also numerous holes for cables, conduits and ducts through which noise is readily transmitted. Suitable stiffening of the panels should preferably be augmented by secondary soundproofing such as application of damping materials. The number of holes through bulkheads must be kept to a minimum and their size as small as possible. To reduce the open area and prevent beating of the objects which pass through a hole against the bulkhead, rubber bushings for moving parts and felt lining for ducts and conduits are highly advisable.

Rigid and stressed floors are light and simple as far as structural design is concerned but from the standpoint of soundproofing they are highly objectionable; they vibrate easily and act as a sounding board. For this reason, the stresses should be taken through horizontal stringers and the floor composed of small panels connected to each other and to the supporting stringers by flexible and elastic means.

Another contributor to airborne noises is the window area. A window held rigidly by a metal frame will act like a loudspeaker diaphragm. Being set into vibration by outside noise or transmitted vibration, it becomes a source of strong noise close to the ear of the passenger. Therefore, it is essential to provide an elastic mounting for the window, by setting it into a channel of extruded rubber, which serves the dual purpose of absorbing vibration and making the assembly air- and watertight.

The greatest efficiency, however, can be obtained by providing two panes separated by an airspace. The frequent objection that this scheme increases the weight unreasonably is only partly justified. Since the window area is responsible for a good percentage of the noise transmitted into the cabin, appreciably more weight must be provided for the absorption of this noise than is necessary, if the amount of transmitted noise is reduced by a double-pane construction. In addition to its soundproofing value, such a method acts as a very good heat insulator.

Double-pane windshields are being used to some extent on commercial airplanes. Recent investigations have also shown that a combination of plastic and glass panes will protect pilots against injury in case of collisions with birds.[4] Aircraft windows and windshields are still in the experimental stage but it can be expected that the double-pane construction will become standard on post-war transports.

In addition to these considerations, airborne noises can be further reduced by proper design and attachment of accessory equipment within the cabin. It is surprising how much noise one badly rattling bracket can create in an otherwise well-soundproofed cabin. Rattling and buzzing noises may be caused by racks, cabin trim, doors, galley utensils and similar equipment. These noises must be traced, one by one, and eliminated by better and, if necessary, shockproof suspension. Noisy equipment, such as generators or auxiliary engines, should be placed outside of the cabin or properly shielded and soundproofed.

Noise reduction by the methods described above may reach from 29 to 34 db, showing again the need for closest attention to even seemingly unimportant details.

2.6 ENGINE NOISE is twofold: *direct* and *indirect*. The direct noise consists of the clatter of valves and tappets, and the noise contributed by gears, carburetor, supercharger and other accessories. The sum of these direct noises is not very high. As a rule, it can be neglected, particulary, if the engine is located in a nacelle, at some distance from the cabin. In such a case, however, the engine noise might be transmitted into the flight deck through the leading edge of the wing which acts as a speaking tube. This can be avoided by properly baffling or closing it with soundproofing materials between inboard engines and fuselage.

The indirect noise of the engine is a more serious problem. As the engine transmits vibrations to the cabin structure, it causes drumming and rattling which is an important contributor to the overall noise level. This is greatly reduced by shockproof or elastic mounting which is employed in practically all modern airplanes. The noise reduction thus obtained may be as little as 5 and as much as 15 db, depending on the efficiency of the installation.

2.7 AERODYNAMIC NOISE is caused by motion of the rapid air stream over the airplane structure. This noise can be decreased only by proper aerodynamic design which is essential anyway in order to minimize drag. If sharp corners, protuberances, and such drag-inducing parts as struts and wires are avoided, as is the case in most modern airplanes, the aerodynamic noise is automatically reduced by from 10 to 15 db.

2.8 SUMMARY OF PRIMARY SOUNDPROOFING. If the principles of primary soundproofing are applied to the fullest extent, the order and magnitude of the various airplane noises, as shown in section 2.1, will change considerably. On the basis of the data for noise reductions which were said to be obtainable by efficient design, the previous list of noise sources and approximate levels can be revised as follows:

Propeller	100 to 104 db
Exhaust	100 to 104 db
Engine Noise	89 to 99 db
Aerodynamic Noise	79 to 84 db
Airborne Noise	74 to 79 db
Ventilating Noise	72 to 76 db
Total Noise	104 to 108 db

Consequently, primary soundproofing can result in a reduction of about 16 to 20 db. This figure is very gratifying but a noise level of 104 or even 108 db is still very much above the level of comfort. A further reduction of 20 or, better still, 25 db is necessary. This must be achieved by secondary soundproofing.

3.0 SECONDARY SOUNDPROOFING

The task of the soundproofing engineer during the primary stage of soundproofing is principally that of a consultant: He does not design propellers, exhausts or fuselages but rather advises the various design groups of certain features which will contribute to the reduction of noise. It is the responsibility of the individual designers to incorporate these suggestions as far as possible although other considerations might prevent strict observance of the laws of soundproofing. Possible increase in weight, such as by addition of stiffeners, shock mounts and the like, are charged to their groups.

In secondary soundproofing, the engineer-in-charge is entirely on his own. He is given specifications for noise levels in various portions of the ship and must obtain these levels within given limits of weight, starting from noise levels which he inherited. Further limitations are imposed by the requirement that his installation shall not interfere with the characteristics, operation and handling of the airplane and its flight or military accessories, nor impede the movements of passengers and crew. In view of these multiple difficulties it is helpful to adopt a definite procedure which starts with the writing of specifications and ends with the last test flight.

3.1 SOUNDPROOFING SPECIFICATIONS. Just as individuals react differently to the sensation of noise, the ideas of what constitute acceptable noise levels under various conditions may be far apart. Consequently, the specifications for desirable levels in a passenger cabin, flight deck, crew quarters and other portions of the ship change with practically every

government agency, airline and aircraft manufacturer. A contributing factor in this respect is the rather limited knowledge of the problems connected with soundproofing and the eternal human ambition to get much for little or, in this case, very much noise reduction for very little weight.

Simultaneous specification of both maximum permissible noise levels and weights is often impossible because it is usually not known how much of a reduction is necessary to achieve the specified level. Consequently, one of the two factors should be only approximated. As a rule, specifications should apply only to the noise level in commercial planes, and only to weight in military planes.

If it is desired to obtain certain noise levels, at optimum but not specified weight, what should be considered to be "reasonable" specifications? In view of the difference in opinion in this respect, it is difficult to establish rigid rules. However, the following ranges appear to be desirable for various portions of a plane at normal cruising speed:

Passenger Cabin	75- 80 db
Control Rooms	80- 85 db
Flight Deck	85- 90 db
Military Cabin	85- 95 db
Lavatory on Airliner	90- 95 db
Crew Quarters	90- 95 db
Unoccupied Portions of Fuselage	95-100 db

(The reason for a small amount of soundproofing in non-occupied portions of the fuselage, particularly by means of vibration damping, is to facilitate and lighten the installation in adjacent, occupied spaces.)

The average noise level on commercial planes, as taken from the above list, should range from 85 to 90 db while, on the military plane, a range of from 90 to 95 db would be acceptable. On the basis that, after primary soundproofing, there still exists a noise level of 104 to 108 db, and even higher on military planes, the previously mentioned figure of 20 to 25 db average reduction required by secondary soundproofing still holds true.

3.2 SOUNDPROOFING PROCEDURE. After the soundproofing engineer has studied the specifications, he must decide on what course of action to take. He might find it preferable to adhere strictly to the weight limit and let the noise levels take care of themselves. A sample calculation of this kind will be made later.

In other cases, it is mandatory to obey the requirements for noise levels, and increases in weight either must be taken into account or compensated for by reducing the allotments to other groups. The question now arises as to how much noise reduction is necessary for the various portions of the airplane. In order to find the answer, it must be ascertained first what the original noise levels in these portions are and what frequencies predominate.

Even if the suggestions of the soundproofing engineer have been followed by the other design groups and a fairly good job of primary soundproofing has been done, the resulting noise levels within the cabin can still be merely assumed but not accurately calculated. In addition, there may be innumerable sources of noise which cannot be anticipated during the design stage. Thus there is only one way of finding the desired information and that is by a test flight in the completed plane without any secondary soundproofing.

During this flight the noise levels and their predominant frequencies are measured in various parts of the cabin by means of a reliable sound-level meter. Sources of noise such as rattles and drumming are investigated and other conditions noted which can be remedied by primary soundproofing.

Thereupon, recommendations are made and, after the changes have been incorporated, a second test flight is undertaken to investigate how much the noise levels have been reduced. The data obtained during this flight are usually conclusive enough to proceed with the calculations.

The designer has now a list of both the existing and desired noise levels at all stations requiring treatment, including the distribution of frequencies, and can thus establish the required noise reductions in terms of decibels.

As will be remembered, the basic relationship between noise reduction and the absorbing power necessary to obtain such a reduction is given by the equation:

$$\text{Noise reduction (db)} = 10 \log \frac{C}{T} \qquad (2)$$

in which C is the total absorbing power of the cabin or the sum of all areas times their absorption coefficient, and T the transmittance, or the sum of all areas times their transmissivity.

This formula shows clearly that the magnitude of the achieved noise reduction depends as much on increase of absorbing power as reduction of transmission. As a scheme which is very efficient for the latter is not, of necessity, equally suitable for absorption, it is necessary to find a compromise which yields the desired noise reduction at the minimum weight and with the least complications. Although it is obvious that neither of the two factors can be neglected, opinions vary as to which is the more important one. For his part, the author prefers to place the main emphasis on absorption.

If it is assumed that the transmittance cannot be changed, and its value has been found or estimated to be about 1.0, then the above formula becomes:

$$\text{Required Noise Reduction (db)} = 10 \log C$$

Since the noise reduction is given, C can now be calculated. For instance, the existing noise in a particular compartment is 103 db but is specifified not to exceed 80 db. This requires a reduction of 23 db. Then:

$$23 = 10 \log C$$

and:

$$C = 200 \text{ sabines}$$

The average absorption coefficient equals the number of sabines divided by the total area, because, by definition:

C = area in square feet × absorption coefficient

Assuming that the areas of the walls, floor and ceiling of the compartment amount to 400 square feet, then the average coefficient must be not lower than 0.5 in order to obtain an absorbing power of 200 sabines or a noise reduction of 23 db. This calculation, incidentally, does not consider the absorbing power of occupants, chairs and other absorbing media. If it were desired to reduce the noise level another 3 db, it would be necessary to double the number of sabines which is explained by the logarithmic relationship between decibels and sabines.

If the transmittance of the room can be ascertained, it is possible to calculate the noise reduction quite accurately although such accuracy is usually of little value since too many factors are variable or based on assumptions. A very good example of such a calculation has been presented by D. C. Greenwood in an excellent article on aircraft noise which appeared in the magazine "Flight." Because it illustrates the calculation of both transmittance and absorption for a specific case, it is repeated below:[8]

Areas and Coefficient of Absorption of Cabin:

Component Surface	Area (sq ft)	C at predominant frequency	Absorption = C×area
Ceiling	220	0.80	176.0
Front Bulkhead	42	0.85	35.7
Side Walls	230	0.78	179.5
Rear Walls	63	0.85	53.5
Rug	30	0.28	8.4
12 passengers at 3 sabines each	—	—	36.0
12 chairs at 2.8 sabines each	—	—	33.6
Parcels, curtains	—	—	13.0

Total absorption = C = 535.7 sabines

Areas and Transmissivities of Cabin:

Component Surface	Area (sq ft)	T	Transmittance = $T\times$area
Cabin, inc. floor	800	0.000675	0.5400
12 windows at 2.25 sq ft	27.5	0.0087	0.2405
Doors (well fitting)	24.0	0.002	0.0480

$$\text{Total transmittance} = T = 0.8285$$

$$\text{Noise Reduction (db)} = 10 \log \frac{C}{T} = 10 \log \frac{535.7}{0.828} = 26.3$$

If this reduction should not be sufficient, it is necessary either to decrease the transmittance, which is usually not desirable, or to increase the absorption. Since the area is constant, the average absorption coefficient must be increased by heavier soundproofing which, in turn, increases the weight.

If, however, the reduction should prove to be greater than necessary, some of the soundproofing should be removed, thereby reducing its weight.

Once the necessary absorption coefficients are known, the proper materials and methods, as described shortly, are selected to achieve the calculated number of sabines. During all of these calculations it should not be overlooked that vibration damping is an integral part of the soundproofing scheme and must be included in calculating absorption and weights.

The final task of the soundproofing engineer is to specify the selected materials and methods and to issue instructions for their correct application. After the installation is completed, the thus soundproofed airplane should be testflown again and measurements made to ascertain whether the achieved noise levels are in accordance with the specifications. In most cases, only minor rearrangements are necessary and, after the second test flight, the soundproofing installation should be ready for inspection.

It is advisable to record all data obtained throughout the entire procedure and to file them for handy reference. They will assist not only in quickly explaining and correcting unexpected noises in the one or the other production model of the soundproofed prototype, but also in adding to the still small store of knowledge for future installations.

3.3 SOUNDPROOFING MATERIALS. The peculiar conditions existing on an airplane make it extremely difficult to find suitable materials for soundproofing which meet all of the many essential requirements. It is only recently that such materials have become available. Intensive research continues to improve their properties further. Even at the present stage, these materials make it possible to obtain an efficient installation at acceptable weights, so long as they are intelligently selected and applied.

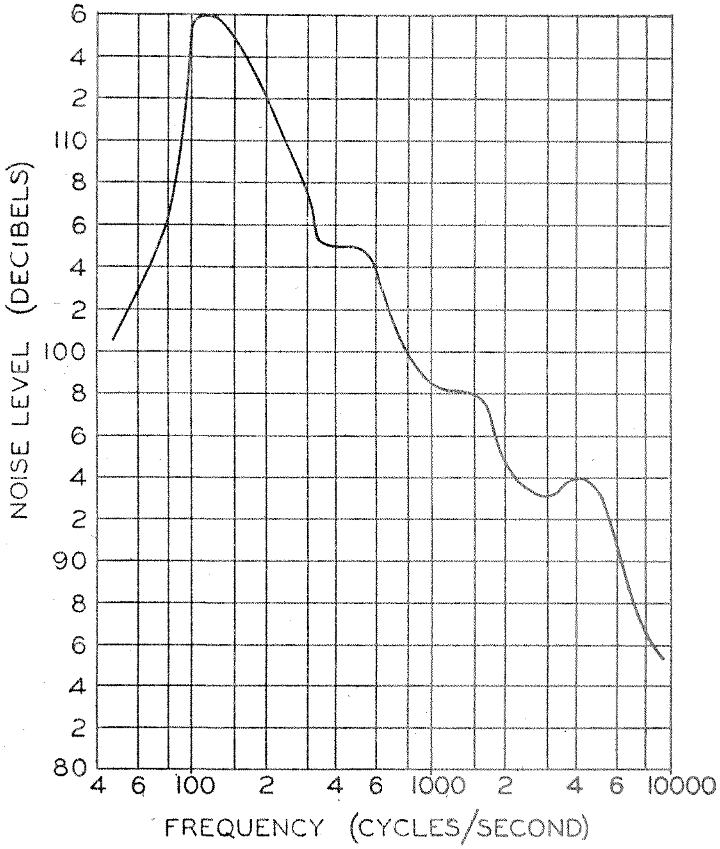

Fig. 119

3.31 *Requirements.* To be suitable for use on aircraft, a soundproofing material must comply with numerous conditions. First, it is not sufficient that its absorption coefficient is very high at one frequency and low at another which may be the more important one. As can be seen from Fig. 119, which represents a frequency analysis of noises on aircraft, most of the noise is contributed by frequencies ranging from 50 to 350 cycles/sec. With increasing frequency, the percentage decreases rapidly. The various humps shown in the curve are explained by the existence of harmonics or resonant frequencies. On the other hand, most sound-absorbing materials are more efficient at the higher frequencies. Unless materials can be found which have reasonably good absorption at low frequency, more weight must be expended to obtain the necessary absorption.

Next, the soundproofing material must be extremely light and have a particularly high soundproofing value per unit weight. This requirement is difficult to meet. The material must also be a very good heat insulator, so that it serves a dual purpose.

The third requirement demands that the material is highly water-repellent. Otherwise, it would quickly soak up enough moisture to destroy its sound- and heatproofing qualities and multiply its weight several times. It is further mandatory that the material can be flameproofed easily without losing its insulating properties. Because materials of this kind are quite fluffy, a spark might suffice to set the entire plane on fire, unless the material is flameproofed.

Soundproofing materials must be protected against vermin and rodents. In addition, they must withstand deterioration, require little or no servicing, be readily applied and, finally, easily shipped without damage.

3.32 *Kapok.* Fortunately, nature has provided a material which fully meets all of the above requirements: *kapok.* A very complete discussion of the culture and uses of kapok has been made by S. J. Zand in his interesting book "Kapok."[5]

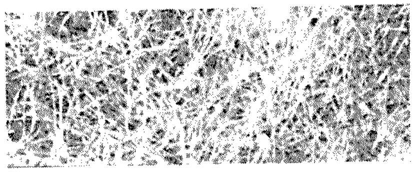

Fig. 120

A microphotograph of Kapok Felt (Fig. 120) reveals some of its many characteristics. Its sound absorption properties at low frequencies are higher than those of any other material known.

Kapok is very light and may weigh as little as 1 lb/cu ft. Figure 121 shows a square foot of "K" Felt, ½″ thick, on a scale. Covered by a waxy substance, called Cutine, which is non-hygroscopic it is also naturally water-repellent. These properties make kapok an excellent material for use in life preservers, life rafts, sleeping bags and even clothing. If used in life preservers, kapok will retain its buoyancy, which is many times its own weight, for a long time before it becomes too heavy to float under load.

Kapok can be flame-proofed easily without affecting its insulating properties. The methods used are trade secrets but normally employ synthetic, borophosphate resins which are liquid, odorless and non-toxic, and provide a glass-like coating. The American Felt Company states that their flame-proofing agent is non-dusting, difficult to wash out and also acts as moth-proofing. Kapok is highly vermin-proof and resistant to deterioration. In regard to handling it is easy to apply and to ship.

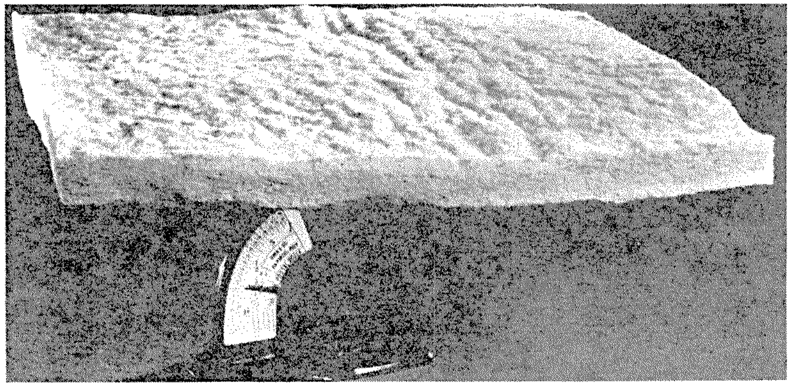

Fig. 121

The suitability of kapok as soundproofing material has long been recognized, but, up to a short while ago, it has been quite a problem to manufacture kapok batts and felts commercially. By now, a number of companies produce soundproofing materials made from kapok which will be briefly described in the following.

3.33 *Dry-zero* is the first kapok insulator and was put on the market in 1921 by the Dry-Zero Corporation. It is a kapok blanket made by an ingenious process of shooting the kapok fibre from a nozzle by pressure against a rotating wheel.[5] The sheet is then enclosed in burlap, cheesecloth or similar materials. Its coefficient of absorption is very high, particularly in considering its low weight of 2½ to 3 pounds per cubic foot. Dry-Zero has been used extensively for thermal and acoustical insulations. The curves shown in Fig. 122 give the sound absorption coefficients for some of the Dry-Zero products at different frequencies. The coefficient for high-grade Hairfelt has been included for comparison. The letters identifying the curves denote the following products, listed with their weights and maximum moisture absorption:

Curve	Material	Weight lb/cu ft	Maximum Moisture Absorbed from Atmosphere, %
A	Hairfelt	8.0	18
B	Dry-Zero in pliofilm, not flame-proofed	2.1	2
C	Dry-Zero in burlap, flameproofed	3.0	6
D	Dry-Zero in muslin, flameproofed	3.0	5
E	Prime Java Kapok, not flameproofed	3.2	4
F	Dry-Zero in burlap, flameproofed	2.6	7

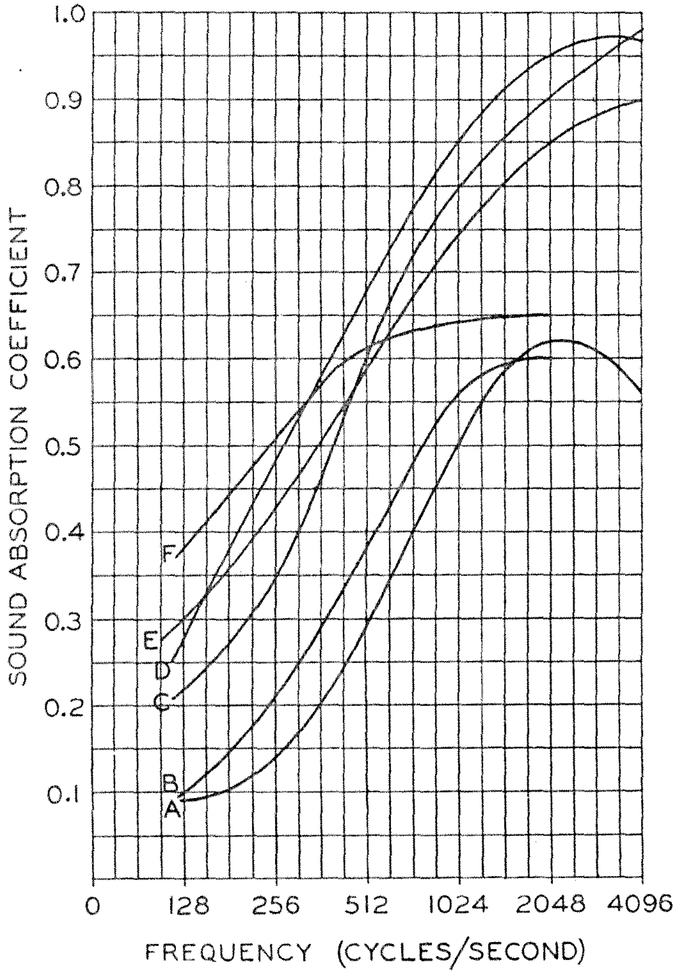

Fig. 122

3.34 *"K" Felt,* a product of the American Felt Company, is a felted combination of 40% kapok, 30% cotton and 30% wool. It is manufactured in rolls about 24 yards long and 72 inches wide. Its thickness ranges from ⅛" to ½", in ⅛" steps. It can be cut to size or templates easily and suspended like a curtain to provide floating layers. Binding of edges is not necessary as it is a true felt.

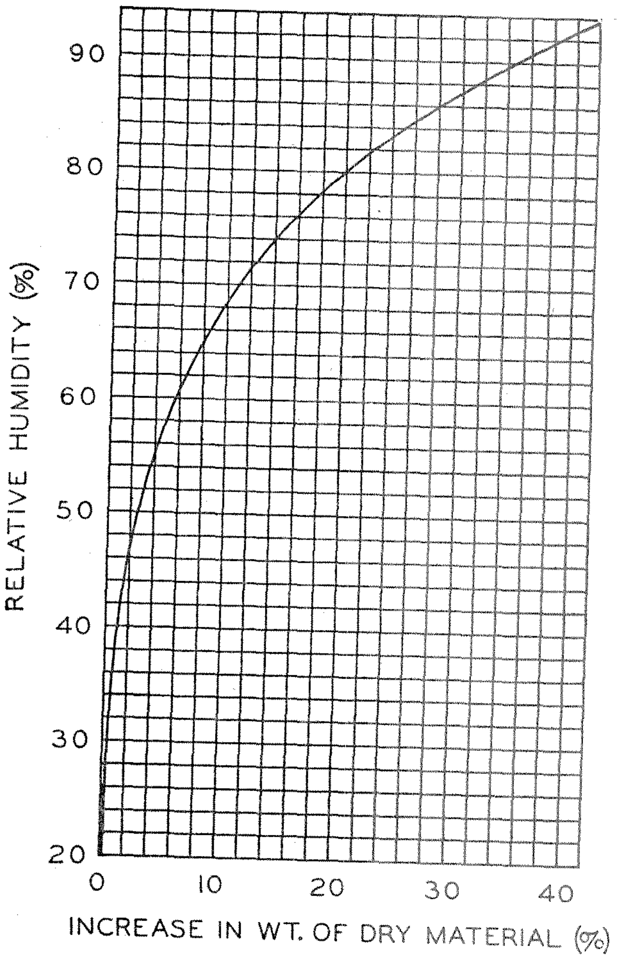

Fig. 123

It has an average specific gravity of from 0.081 to 0.090 so that, for instance, a square foot of the ¼" material weighs about 0.111 pounds. This weight is a little more than some other kapok products;

however, both its heat and sound insulating values are excellent and, in some respects, unexcelled.

The heat conductance of "K" Felt has been discussed in a previous chapter (see Fig. 47). Its weight increase with increasing relative humidity is shown in Fig. 123. The sound absorption coefficients of "K" Felt for different thicknesses and various frequencies are illustrated in Fig. 124. The curves are for the following thicknesses:[6]

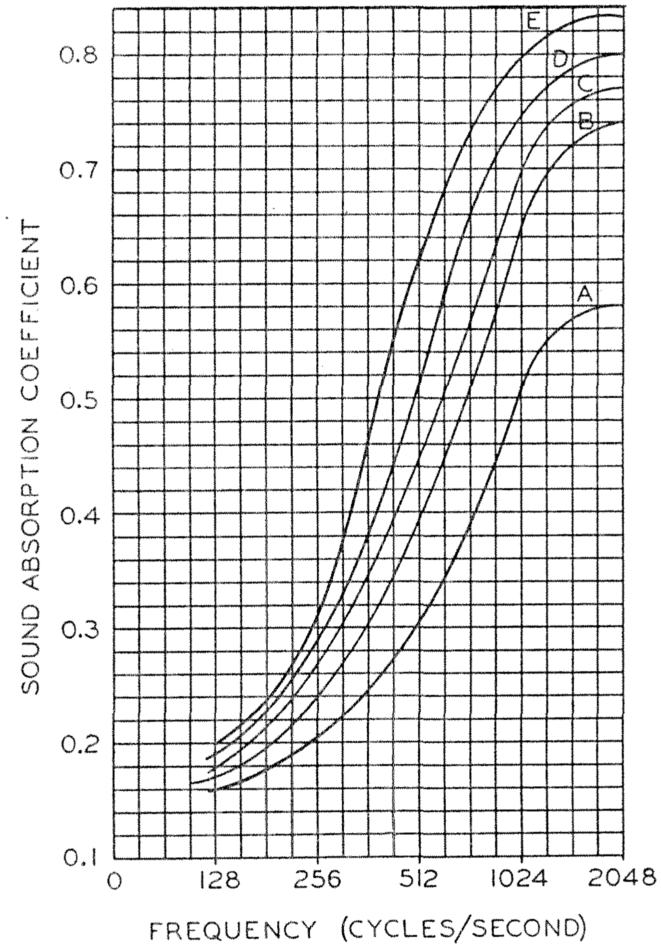

Fig. 124

Curve A	3/16″
Curve B	1/4″.
Curve C	5/16″
Curve D	3/8″
Curve E	1/2″

3.35 *Tropal* is an interesting soundproofing material, which is used in England. It consists of pure, prime Java kapok, comes in blanket form from 3/16″ to 2″ thick and weighs only 1.5 to 2.5 pounds per cubic foot.

The kapok is sewn together with almost invisible stitches by means of a special machine, so that the result is a very fine and elastic blanket, especially suited for floating layers and vibration damping.[5]

3.36 *Seaman Paper Company Products.* In 1932 George Seaman devised a process of commercially producing a material which contained between 70 and 85% prime Java kapok and was introduced under the name of SEAPAK. This material is the original product which the Seaman Paper Company manufactured for aircraft insulation and has, since then, been augmented by numerous variations, some of which are shown in Fig. 125.

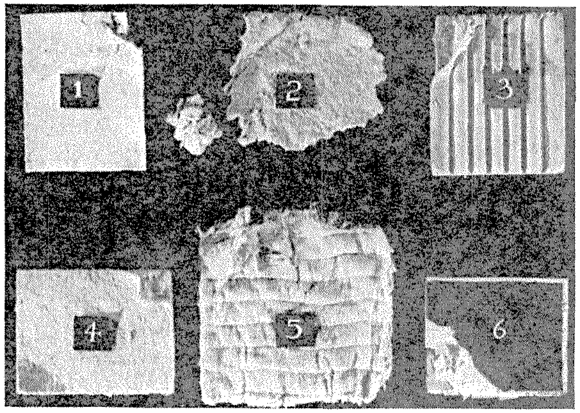

Fig. 125

"Type A" Seapak is the basic material from which most other types are made. Its specific weight is 0.083. The base product has a thickness of ⅛″, and heavier sections are combined by gluing several layers together. The sound absorption coefficients of such combinations are shown in Fig. 126, in which curve *A* refers to one layer, ⅛″ thick, cemented to the wall; curve *B* to two layers, of ¼″ total thickness, also cemented to the wall, and curve *C* to two layers of the same thickness but spaced 1″ from the wall.

Seapak can be strengthened by lining it with rope (Type R) or with rope on one side and Latex on the other (Type RX). These materials are used for damping where vibrations are particularly severe.

In 1934 a process was developed by which it became possible to corrugate "Type A" Seapak. This product has excellent absorption characteristics as shown in Fig. 127. Curve *A* refers to two layers of "Type CJ" which has large corrugations (11 to the foot), curve *B* to a single layer of "Type CS" which has small corrugations (36 to the foot), and curve *C* to a single layer of "Type CJ."

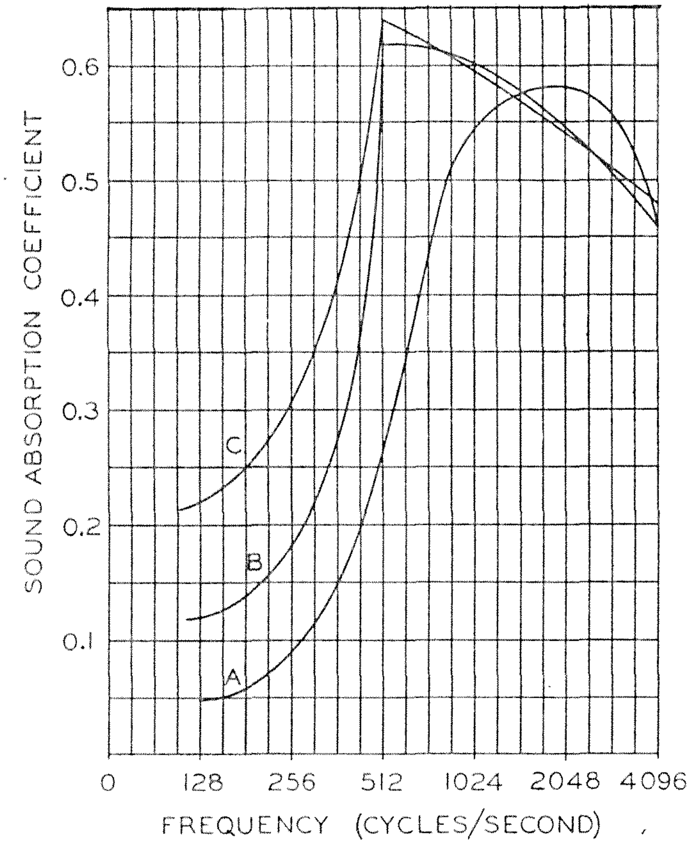

Fig. 126

The corrugated Seapak is used where space limitations do not permit insertion of dead-air spaces but where good absorption at both high and low frequencies is necessary. Other uses are for vibration damping on firewalls and in ducts. Protection by wire mesh is necessary in the latter cases.

A further development of Seapak is KWILKO, a fluffy, light-weight and flexible batt or blanket of 100% kapok sewed between cheesecloth.

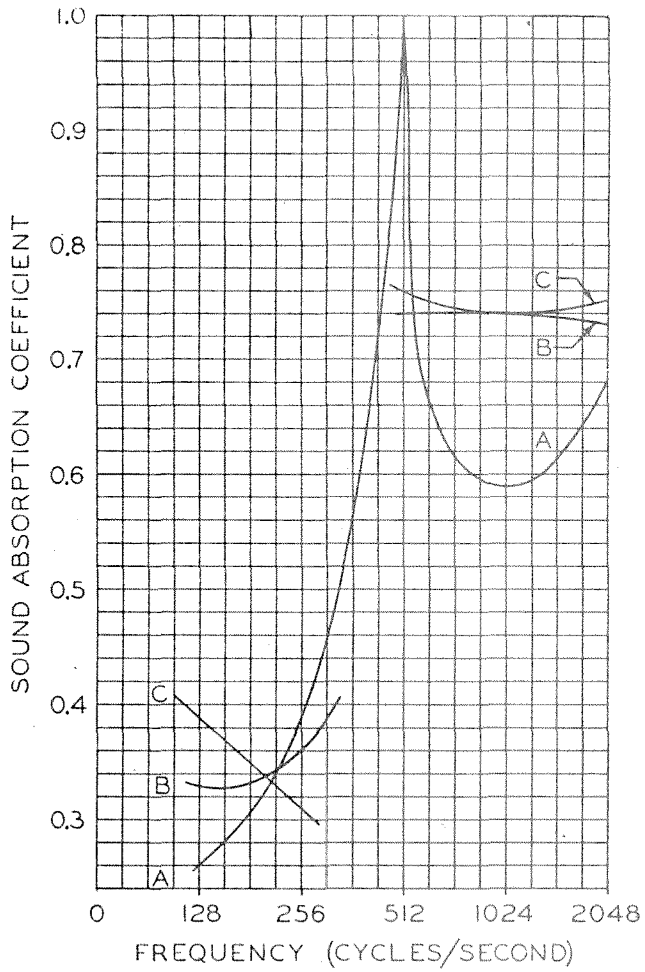

Fig. 127

A cloth covering may be stitched to this combination to provide the cabin trim. Like all other Seapak products, it is moisture proof and flameproof.

Thickness, weight and sound absorption coefficients for the two most commonly used types of Kwilko are shown below:

Thickness	Weight per sq yd	Sound Absorption Coefficient at various frequencies, cycles/sec				
		128	256	512	1024	2048
1/4″	.54 lb	.11	—	.45	—	.76
1/2″	.72 lb	.08	.18	.70	.93	.82

A more recent development is SKYFELT, a felted product with a content of kapok, wool and cotton. "Skyfelt Special" is particularly light while "Skyfelt Regular" is somewhat heavier but has more tensile strength.

Thickness, weights and absorption coefficients are shown in the table below. (Weights given are only approximate since they vary for different runs.)

Material	Thickness	Weight per sq yd	Sound Absorption Coefficient at various frequencies, cycles/sec				
			128	256	512	1024	2048
Skyfelt Special	1/4″	0.70 to 0.75 lb	0.07	0.20	0.61	0.91	0.78
Skyfelt Special	1/2″	1.60 to 1.70 lb	0.14	0.45	0.96	0.97	0.83
Skyfelt Regular	1/4″	0.90 to 0.95 lb	0.08	0.26	0.80	0.95	0.76
Skyfelt Regular	1/2″	1.75 to 1.80 lb	0.14	0.45	0.96	0.97	0.83

Seaman Paper Company also manufactures aircraft rugs with high sound absorbing qualities. These rugs consist of a layer of Skyfelt, from 1/4″ to 5/16″ thick, which is attached to a quality mohair. The basic size is 54″ when supplied in rolls.

3.37 *Miscellaneous Materials.* The increasing problems of soundproofing on aircraft have induced a number of other companies to experiment with light-weight and efficient soundproofing materials, using fibers made from glass or synthetics. Little information is available concerning such developments at this writing. However, it can be expected that products surpassing the properties of the materials described above will be offered by all of the interested companies in the near future, especially in view of the fact that it has recently become necessary to restrict the use of Kapok for the duration.

3.40 METHODS OF SECONDARY SOUNDPROOFING. The magnitude and frequency of vibrations and noise differ considerably in various parts of an airplane cabin. Also, desired noise levels are not the same throughout the fuselage. Although it would be ideal to keep the noise level at 70 db or even less in the entire plane, such a scheme would be far too expensive in terms of weight to make it practical, and there is no need for it.

As a result, the necessary noise reductions for individual stations may vary from 5 to 30 db, with predominant frequencies ranging from 50 to several thousand cycles per second. This requires the most economical selection not only of the most suitable materials but also of their proper combination and method of application.

Although there are several schools of thought as to what methods are the best in specific cases, the basic principles remain the same, namely to dampen vibration, impede transmission and increase absorption with the least amount of weight.

At the present time, there are five fundamental methods employed in the secondary soundproofing of aircraft which may be designated as the *damping, light, medium, heavy,* and *special* methods.

3.41 *Damping Method.* As its name implies, the damping method has only one purpose: to dampen out vibrations which, in turn, would create noise. It consists merely of treating areas given to vibration and drumming, such as the bulkhead webbing, with an asbestos spray which is light, washable and paintable. The material may be sprayed on thicker in the center of the panel and thinner towards the edges. However, it is simpler to provide an even coat with a thickness of approximately 0.020″. Surfaces must be thoroughly cleaned before being treated.

A widely used damping paint of this type is the "B.C. Sound Deadener" which is manufactured by the Billings-Chapin Company. Its weight is about 0.07 lb/sq ft.

Damping can also be effected by gluing to the skin thin sheets of mica or similar materials. In a recent development, drumming of the skin is minimized by making it from one or more layers of fiberglass glued between two thin sheets of aluminum. This combination has not only excellent damping qualities but the same or even greater strength than an equivalent thickness of plain aluminum.

The damping method provides, of course, no absorption and is efficient only in damping comparatively light vibrations, unless it is augmented by other materials. However, it provides a very light and convenient means for simple vibration problems.

3.42 *Light Method.* As vibrations become more severe and a certain amount of absorption is desired, the *Light Method* must be employed in which such materials as "K" Felt or Seapak are glued to the metal. The layers are normally from ⅛″ to ⅜″ thick, and are attached by cements like Vultex or Amplex. Since the weight of the cement is not entirely negligible in treating large areas, it is sometimes applied in strips or dots. However, it is important to keep the damping material and metal in close contact for best efficiency and, for this reason, it is advisable to cover the entire area with a thin film of the cement. It is applied to both of the surfaces which are to be glued together and permitted to dry for a few moments. Then the soundproofing material is carefully put in place, with only very slight pressure. Figure 128 shows such a treatment for the ceiling of a commercial airliner. The material used is Seaman's "Q-3" which consists of three layers of Seapak, quilted between cheesecloth.

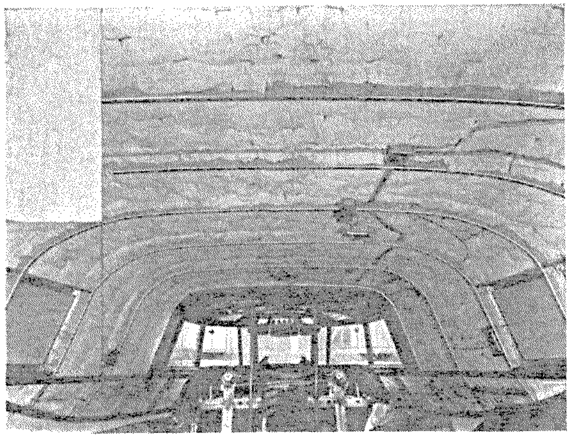

Fig. 128

Stringers, braces, shelving and other obstacles along the walls often make the proper attachment of damping materials quite difficult. This is illustrated in Fig. 129 which shows the cementing of "K" Felt to the fuselage of a military plane built by Lockheed. The worker wears a mask to protect him against the fumes of the evaporating cement.

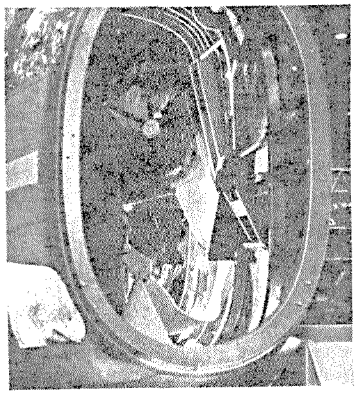

Fig. 129

The damping material may be covered by a thin layer of cloth or fabric stitched or glued to it. In intermediate cases, it sometimes suffices to cement the cloth directly to the metal.

3.430 *Medium Method* is an elaboration of the previous one in that it adds another layer of soundproofing material which is separated from the first one by a dead-air space. This method is used in the middle and aft portions of commercial cabins and at least the forward portion of military planes. It is very efficient in damping rather severe vibrations and has good absorbing qualities. A cross section through such an installation is shown in Fig. 130. Felt or quilted Seapak is glued to the skin and, wherever possible, over stringers. Leaving an air space of about 1 inch, there is a second layer, consisting of such materials as Kwilko or a felt of low density which is covered with a fabric.

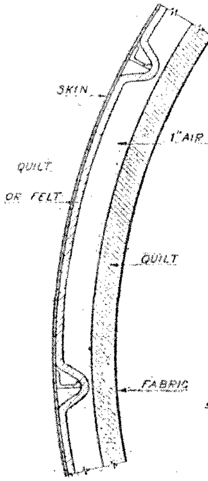

Fig. 130

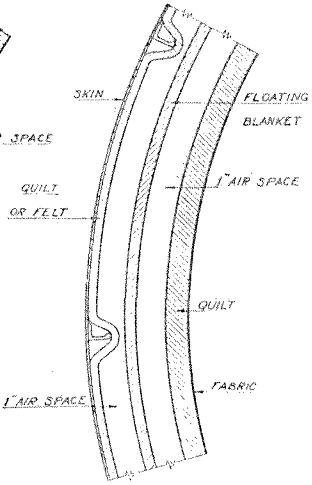

Fig. 132

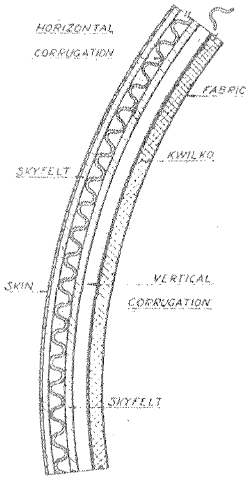

Fig. 133

3.431 *Purpose of Air Space.* Three questions arise in connection with this construction. First, exactly what and how does the air space contribute to the efficiency of the installation? A diligent study of the existing literature yields little information in this respect. It is generally agreed that the insertion of air spaces will result in considerable improvement of a soundproofing installation because this has been proven by actual measurements. However, there are no conclusive data which would permit the establishment of simple calculations for their acoustical properties. This is not true for air spaces in thermal insulations for which ample theoretical and empirical information is available.

Since air offers very little resistance to the flow of sound, as compared to other materials, the actual sound absorption of a 1″ air space is so small that it can be neglected. Hence, the value of the space lies mainly in its damping properties which is the reason for its use in acoustical installations

As was shown, most of the aircraft noise is in the low-frequency band and most of that exists in the forward part of the cabin which is close to the main source of this low-frequency noise, namely the engine with its accessories, including propeller and exhaust. In looking up the sound-absorption coefficients of the various soundproofing materials, which were listed above, it becomes apparent that they are quite high between 1000 and 4000 cycles/sec, then taper down with decreasing frequency to reach a medium value at about 500 cycles/sec. Further decreasing almost linearly, they reach a low at 128 cycles. (In acoustics, intermediate steps in the audible frequency range are usually selected as fractions or multiples of 256 cycles/sec which is very nearly the frequency of middle *C* on a piano.)

If it were demanded that the noise in a cabin after soundproofing should not exceed the specified levels at any frequency, including 128 cycles/sec, it would be necessary to triple or even quadruple the weight of the installation. This would reduce the noise to the desired level in the low-frequency range but very much more than necessary for all other frequencies.

Although the noise absorption of kapok is far greater at low frequencies than that of other materials, there is as yet no kapok or similar lightweight material available which would be more uniformly absorbent over a broader frequency range.

Fortunately, a dead-air space has the property of damping out low frequencies. Consequently, in an arrangment as shown in Fig. 130, the transmission of low frequencies into the cabin will be impeded and noise of similar frequency inside the cabin will not be so easily reflected. The depth of the air space should be sufficient to make it an efficient low-frequency impedance although too much depth would take unreasonably much room. 1″ is normally a good compromise.

3.432 *Selection of Trim Fabric.* The second problem which the discussion of the *medium method* brings up is that of the type of trim fabric which should be used. The normal tendency is to cover the soundproofing installation with a doped fabric; leatherette or similar material which has the advantage of better appearance, affords more protection to the sensitive soundproofing materials, assists the illumination by increasing light reflection and can be easier cleaned. Also, it is preferable from the standpoint of thermal insulation.

On the other hand, a stiff and non-porous material reflects sound very well, with the result that the sound waves are being thrown back and forth between the walls until they die a natural death caused by progressing attenuation. This phenomenon is called *reverberation* and is often experienced in rooms which are bare and otherwise lack absorbing power. If a soundproofing installation is thus covered, its purpose is largely defeated because it does not permit the sound waves to reach the millions of little traps which are to kill the sound, namely the pores and pockets within the materials. Too, low-frequency noises are easily transmitted.

Considering the great intensity of the noise and the small area and weight available for absorption, every helpful detail is highly important. For this reason, the cabin lining should consist of a porous, durable cloth. Such materials are available commercially, are of light weight and pleasing texture, and can be readily cleaned by brushing or light vacuuming. It is surprising to experience how much difference a change from a stiff to a flexible, porous lining will make.

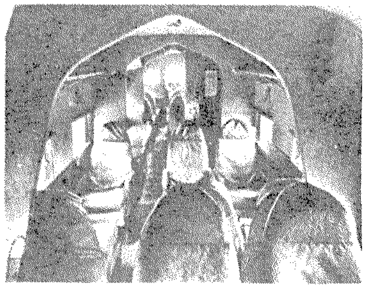
Fig. 131

This concept is by no means new. One of the first airliners equipped with a scientific soundproofing installation, the Curtiss Condor, used such a trim fabric in its cabin (Fig. 131).

3.433 *Humidity Control.* A third problem which is introduced by the *medium method* is that of humidity control. The water-repellent properties of soundproofing materials for aircraft have been emphasized repeatedly. Even the best materials will soak up enough water eventually to increase their weight considerably and so fill the pores as to affect their sound- and heatproofing qualities. According to R. L. Ellinger,[7] investigations conducted by T.W.A. showed that the weight of a conventional soundproofing installation in a four-engine, supercharged plane increased about 35% or 160 pounds in 18 months of operation. In a non-supercharged, two-engine airliner the increase was only 28% in five years. These figures check quite well with what had been said before. On the other hand, there are reports that soundproofing installations have doubled and even tripled their original weight within very short periods. The explanation of these seemingly contradictory experiences is very simple.

Since there is usually a considerable temperature difference between the warm cabin and the cold outside air, the moisture created by passengers and otherwise existent in the cabin will condensate on the cool skin. If the skin is covered with a moisture-repellent soundproofing material, the water droplets will collect on its surface and either trickle down or collect in pockets and similar places. This is particularly serious in cases where a dead-air space is formed by water-repellent materials because the moisture remains trapped.

As the outside temperature increases or greater altitudes are reached where humidity and pressure are low, the moisture tends to evaporate again but more of it will stay within the soundproofing installation than will get out. The remaining water gradually dissolves the substance which makes the material waterproof and begins to fill out its pores. Thus, the trapped water has two deleterious effects: It increases the weight of the installation unreasonably and accelerates the loss of its water-repellent and, with it, other valuable properties.

So, it is extremely important to vent a dead-air space to the outside and permit condensate, which has formed, to drain out readily. One difficulty in this respect is the fact that, during flight maneuvers resulting in high gravitational forces, the water which might have trickled down into the drain will be splashed all over the air space again and settle on the layers. This can be prevented by making the air alive, that is, giving it a slight motion.

In such a scheme, the air space connects to a spill, preferably at the bottom of the fuselage, through which the air is drawn out and spilled overboard, together with much of the moisture. It is replaced by warm cabin air which is sucked into the air space through the porous lining. This has the added advantage of warming the material on the skin and thus decreasing condensation, besides adding to the thermal insulation. Care must be taken to prevent pockets near the outlet in which condensate might form and remain trapped.

Occasionally, it is specified that the soundproofing installation is removable so that it can be inspected and dried. This scheme should be discouraged because it may increase the weight by as much as 60 to 70 pounds and result in a loss in noise reduction of from 3 to 6 decibels.

3.44 *Heavy Method.* The noise in the forward portion of the cabin may be so loud that the *medium method* does not suffice to obtain the required noise reduction. More absorption as well as more protection against low-frequency vibrations must be provided which leads to the *heavy method.*

In this method a second air space is added as can be seen in Fig. 132. The treatment of skin and cabin lining is the same as in the *medium method,* although the thicknesses of the materials can be increased. Two air spaces, of 1″ depth each, are formed by insertion of a freely-

floating layer which is suspended between the other two layers. It is from ⅛″ to ¼″ thick, and consists of such materials as Seapak, which is quilted between cheesecloth, or "K" Felt.

A common method of attaching the floating blanket is to suspend it in cross-lacing. Other means of attachment consist of stretching the blanket over a frame. It is important that it can vibrate freely without transmitting such vibrations to one or both of the other layers so that the vibrations may be readily dampened by the air spaces.

This construction is fairly heavy and space consuming. However, it has excellent sound- and heat-absorbing values and is the best means known to deal effectively with the severest vibrations and noises on an airplane.

The remarks concerning porosity of the lining and the need for venting the air spaces which were made in discussing the *medium method,* apply, of course, to this method as well.

3.45 *Special Methods.* In addition to the methods described above, there are several others which are based on similar considerations. The purpose of these variations is either to decrease the thickness of the insulation, facilitate its installation or otherwise improve it. Weight savings are seldom achieved because the absorption coefficient of a combination usually remains the same, no matter what its particular construction is.

One of these methods is the SEAMAX panel, shown in Fig 133, which was developed by cooperative efforts of the Seaman Paper Company and the author. The purpose of this panel is to provide all of the components needed in a soundproofing installation in one piece which can be readily cut to any desired size. On the skin side is a layer of Skyfelt to which a layer of corrugated Seapak is attached by stitching or gluing. The horizontally-running corrugations form a small but effective air space. Another air space is created by a second layer of corrugated Seapak, with corrugations running vertically, which is separated from the first one by a Skyfelt layer. The fourth layer is Kwilko which is covered by a porus cotton fabric.

Although none of the layers are actually floating, the separation by Skyfelt prevents most of the vibration from being transmitted by physical contact. The panel is very easy to handle and cemented to the skin, requiring no further means for attachment. The construction shown in Fig. 133 has a depth of only 1½″. In a variation of this design, one of the air spaces and one layer of Skyfelt can be omitted. Thicknesses of the individual layers may likewise be reduced or increased to conform with specific requirements.

Tests conducted showed very satisfying and promising results both as to acoustic and thermal properties, however, research is continuing, particularly in connection with forced ventilation for humidity control.

Another interesting development is the insertion of an "impervious septum" into the soundproofing installation which is believed to reduce greatly transmission at the higher frequencies. An impervious septum is a material of "high flow resistance" which is defined as the ratio between the air pressure difference across the material and the rate of air flow through it. Thin asbestos sheets are often used for this purpose. Opinions as to the advantages of this method are sharply divided and it appears that it is advisable only where reduction in the transmission of high-frequency noise is both necessary and feasible, and moisture control is not affected.

3.46 *Attachments.* In discussing the use of soundproofing materials only little has been said regarding their attachment to the airplane and to each other. Means and methods of attaching airplane fabrics cover an extensive field in itself because there are innumerable, individual problems which change for every new cabin design.

Although there are many types of fasteners, clamps and other devices on the market which are either adaptable to or specially designed for the attachment of such materials, it is entirely up to the engineer to select or design the means which are best suited to his particular case.

As a result of the variety of attachments which are required, no more specific rules can be given than: Always remember the purpose of the material which is to be attached or suspended. Obey the fundamental laws of good soundproofing.

3.5 SELECTION OF SOUNDPROOFING METHOD, either for the entire airplane or an individual compartment, is by no means arbitrary, excepting the decision as to whether there should be any soundproofing at all. This decision is up to the procuring agency or airplane manufacturer and usually based on considerations of weight.

In cockpit-type aircraft, soundproofing is practically useless, but only in the commonly accepted sense. Secondary soundproofing would have little if any value in a fast fighter plane with open cockpit, but what about primary soundproofing?

It has been proven beyond doubt that abnormal noise created by an airplane indicates an inefficiency somewhere. The engine suspension might be poor and transmit harmful vibrations to the structure, or the propeller is badly calculated, or the fuselage vibrates too much under unexpected stresses, or protruberances cause both avoidable drag and noise. For this reason, there should always be at least primary soundproofing; thus, it is advisable to consult a soundproofing expert during design of every airplane. His advice will not only help to reduce the

noise level to some extent and, thereby, achieve at least some comfort without the expenditure of weight, but it may also point out the deficiencies mentioned above.

Secondary soundproofing, on the other hand, should never be undertaken without combining it with primary soundproofing. Once it is specified and the desired noise levels given, the further choice of materials and methods is established within narrow limits.

Materials are selected in accordance with the necessary sound absorption and predominant frequency. Methods are chosen with respect to the required reductions in noise level and severity of vibration.

The following rules pertain to the selection of soundproofing methods in the most common cases:

Drumming:	Spray with sound deadener
Light Vibration:	Sound deadener or ⅛" damping material glued to skin
Strong Vibration:	¼" damping material glued to skin
Light Absorption:	¼" to ½" felt or Seapak glued to skin
Good Absorption and Damping:	Add 1" air space and glue Kwilko to back of fabric
Very Good Absorption and Damping:	Increase air space to 2", divided by floating blanket of felt
Exceptionally Good Absorption:	Increase thickness of individual layers
Bulkheads:	Treat bulkheads in unoccupied spaces with sound deadener; cover bulkheads in passenger cabin with layer of felt and those forward by additional layer of Kwilko. Treat bulkhead sides facing away from cabin with felt, at least ⅛" thick
Walls:	Heavy method for forward part of passenger cabin, medium for aft portion. Walls in flightdeck and control room: light to medium. Crew quarters: light. Toilets: light. Treat walls in baggage compartment with sound deadener.
Ceiling:	Medium method. If too heavy, cover by ¼" to ½" felt or Seapak "Type Q-3" in passenger cabin, ⅛" felt in other occupied spaces of fuselage, sound deadener in the rest.
Floor:	Noise absorbing rugs in passenger cabin, sound deadening paint in rest.
Webbing:	If vibration is strong and within or close to occupied spaces, apply sound deadener or felt, as the case may be.

3.6 WEIGHT CONSIDERATIONS. Not even a woman can be as weight-conscious as the airplane engineer. This applies particularly to the soundproofing group because it is usually expected to achieve more with less weight than most other groups.

Conversely speaking, the product of noise intensities in a cabin and the weight of the soundproofing installation is a given constant for every particular airplane. Reduction of the noise level is accompanied by a corresponding increase in weight and vice versa. This fact had been brought out before when it was shown that the designer can hold himself to only one of the two variables, depending on which is considered to be the more important.

Airline operators will accept apparent loss of income due to somewhat higher weight of comfort accessories, because they realize that increased comfort for passengers is more profitable in the long run. Therefore, the noise reduction in their transports is more important than the weight needed to achieve it.

On the other hand, 10 pounds of dead load represent 30 rounds of ammunition for a .50-caliber machine gun which can easily mean the difference between life and death. Consequently, in allotting a certain weight for the soundproofing of a military airplane, the procuring agency has established the maximum which can be spared for this purpose. The task of the designer is to use this weight wisely in order to approach the desired noise levels as closely as possible but, under no circumstances, exceed the weight limit. The achieved noise levels, then, represent the maximum comfort which can be allowed under the circumstances, and the corresponding specifications merely indicate the relative reductions desired for various portions of the ship. This leads to an entirely different method of calculation: by weight distribution.

In using this method, the first problem is to find a reasonable figure for the weights which should be allowed. Although there are no formulae which permit the approximate calculation of weights for given noise reductions, empirical values indicate that, as a rule, a fairly good soundproofing installation on a commercial airliner weighs from ¾ to 1% of its gross weight. The figure is slightly higher for small planes and vice versa. For military airplanes, a percentage of from ¼% to ½% of the gross appears to be acceptable. The method of designing a soundproofing installation on the basis of weight alone is best explained by the following example:

Assumed that a weight of 120 lb has been allotted for the soundproofing of a two-engine, long-range bomber. Although desirable noise levels have been specified, the weight is not to be exceeded, no matter what the resulting noise levels should be. The primary stage has been completed and many suggestions incorporated which have reduced the otherwise existing noise level. Floors are satisfactory and no weight shall be expended for their further insulation. Mounting of floor boards has not been charged against the allotted 120 lb.

Secondary soundproofing is to be applied to the flight deck, the combined navigator's and radio operator's cabin, crew quarters and three other occupied zones. After studying the relation between the specified levels and the construction of the interior, the following tentative distribution of weights is made:

Flight Deck	25.00 lb
Navigator's Compartment	35.00 lb
Crew Quarters	20.00 lb
Other Three Stations Combined	40.00 lb
Total	120.00 lb

The allotted weights are then expressed in terms of area times unit weight of soundproofing installation per compartment or station. Some experimentation is necessary to stay within the compartment allotments. In some cases, a little weight may be taken from one to make a better insulation for another one. This is continued until all weights have been used up without exceeding the total and even leaving a margin for slight additions after the installation has been test-flown. As an example, this calculation will be carried out for the navigator's and radio operator's compartment.

A rather low noise level is required which was to be expected. This necessitates treatment of the ceiling; however, there are control cables running close to it and it is specified that the soundproofing installation on the ceiling be removable so that there is an easy access to these cables. It is decided to use hinged panels which consist of a frame made from spruce wood, ¾″ by ¼″, and glued together. The fabric is to be stretched over the frame and nailed to its back.

The engine noise is quite high so that the use of an air space is necessary. Bulkheads must be treated quite well since they contain large, thin panels. Walls and ceiling will be treated alike and in the following manner (medium method):

"Type A" Seapak, ⅛″ thick, is glued to this skin by Vultex cement used only in spots for weight economy. Next follows a dead-air space of 1″ depth and then, "Type Q-1" Seapak, ⅞″ thick, with an integral cover of cotton fabric. The area of the ceiling is 15 sq ft and that of the walls 86 sq ft, so that the combined area is 101 sq ft.

Weights of the soundproofing material, per square foot, are as follows:

"Type A" Seapak	0.068
Vultex Cement	0.005
"Type Q-1" Seapak	0.085
Fabric	0.062
Unit Weight	0.220 lb/sq ft

Weight of wall and ceiling treatment: 101 × 0.220 = 22.2 lb.

The panel frames (540″ total length) have a cubical content of 101.3 cu in and a unit weight of 0.016 lb/cu in. Their total weight is:

$$101.3 \times 0.016 = 1.7 \text{ lb}$$

Both sides of the forward bulkhead are sprayed with sound deadener, at 0.07 lb/sq ft, and covered with cotton cloth at 0.062 lb/sq ft, thus giving a unit weight of 0.132 lb/sq ft. The bulkhead has a total area of 32 sq ft. Thus, the weight of the treatment is:

$$32 \times 0.132 = 4.3 \text{ lb}$$

(In calculations of this kind, the last decimal should be rounded off to the next higher value.)

The aft bulkhead is treated in the same manner. Its total area on both sides is 40 sq ft. Therefore, the weight of the treatment amounts to:

$$40 \times 0.132 = 5.3 \text{ lb}$$

Adding these weights, the treatment for the compartment requires 33.5 lb. This figure is below the allotted 35 lb, but does not include weight of the attachments. For this reason, it is advisable to always add a round figure of 10% to the weights thus obtained which, averaged over all figures, leaves weight for attachments, slight differences in weights of soundproofing materials and some margin for possibly required improvements. Adding 10% to 33.5 lb gives 36.9 lb which is a trifle high.

The practice of "stealing" too much weight from other compartments should be avoided; therefore, the design is re-examined for modification. Finally, it appears that the cloth covering on the back of the aft bulkhead contributes the least to the scheme, and the calculation is changed accordingly.

The weight of the treatment for the aft bulkhead is now as follows: The side facing the compartment is treated as before, and the weight is: 20 × 0.132 = 2.7 lb. The opposite side is merely sprayed with sound deadener, at 0.07 lb/sq ft. Then: 20 × 0.07 = 1.4 lb. Thus, the total treatment weighs now 4.1 lb. which represents a saving of 1.3 lb.

Consequently, the weight for the whole compartment has been reduced to 32.2 lb and, after addition of 10% for attachments, amounts to 35.5 lb. This is only ½ lb over the allotted figure and shall be taken into account in view of the fact that the treatment for this apartment is of particular importance.

After this procedure has been completed for all compartments and the weights have been balanced, it is calculated how much noise reduction can be expected and what the approximate noise levels in the

various compartments will be. As an example, the insulation which has just been established for the navigator's compartment will be examined for its soundproofing value.

The absorbing power of the wall and ceiling treatments, which are identical, is:

$$C = A(c_1 + c_2 + c_3 + \cdots) \tag{3}$$

in which C is the absorbing power in sabines, A the combined area of walls and ceiling, and c_1, c_2, etc. the absorption coefficients of the individual layers. Since the absorption of the skin, air space and cloth cover is very small, it can be neglected, leaving a layer of ⅛″ "Type A" Seapak and a layer of ⅛″ "Type Q-1" Seapak. In looking up the absorption coefficients of these materials, it is found that they are identical but range anywhere from 0.08 at 128 cycles/sec to 0.95 at 1024 cycles/sec.

It is certain that most of the noise in this compartment will be of low frequency. However, the damping effect of the air space permits the choice of the coefficient at 256 cycles/sec so that c_1 and c_2 can be conservatively assumed as 0.26 each. Thus:

$$C = A\ (0.26 + 0.26) \text{ and, since } A \text{ was 101 sq ft}$$
$$C = 52.5 \text{ sabines}$$

The absorption contributed by the treatment of the bulkheads and floors is very small. Their absorption plus that achieved by two occupants, chairs and other sound absorbing objects shall be included in a round figure of 10 sabines, resulting in a total absorbing power for this room of 62.5 sabines.

The transmittance into the compartment can be expected to be such that a value of $T = 1.0$ is justified. Then:

$$\text{Noise Reduction (db)} = 10 \log 62.5 = 18$$

The noise level in this area, without secondary soundproofing, would probably amount to about 105 db. A reduction of 18 db decreases this level to 87 db which complies well with the previously suggested range of 85-90 db for flight decks. The reduction is even greater at medium and high frequencies so that the soundproofing scheme, as proposed, appears to be satisfactory.

3.7 MAINTENANCE. The task of soundproofing is not completed with the acceptance flight. In order to retain its properties, soundproofing must be regularly *serviced* just like any other piece of equipment. Maintenance of such installations is very simple and requires little time but, if it is neglected, the low noise levels and weights which have been achieved with so much effort will begin to rise. Following are a few rules for regular servicing which should be observed under all circumstances:

Examine for trapped moisture and make sure that venting is unimpeded. Re-attach corners and edges which have become loose since every square inch of unprotected surface seriously affects the entire soundproofing scheme. In addition, the whole panel might drop off during the next flight. Repair tears and holes by stitching or by taping with light, airplane tape. Avoid bouncing or knocking against fabrics as there may be air spaces behind them. Clean the side facing the cabin by brushing or vacuuming; clogged-up pores decrease the sound-absorbing qualities of the material. Examine the cabin for loose connections, brackets, floor boards and other parts which might cause rattling, drumming or vibration during flight.

4.0 HEATPROOFING

A good soundproofing installation is usually also a good heat insulator while the opposite is not always true. For this reason, the insulation on an airplane is calculated only from the standpoint of soundproofing, and its added use as heat insulation considered a welcome gift.

The heat conductance of most aircraft soundproofing materials is very favorable, and the air spaces used in the better protected areas are as valuable for heat insulation as they are for soundproofing. For the sake of weight economy it would be unwise to add further insulation for heatproofing alone since the savings obtained by the existing installation are usually sufficient except in cases where no soundproofing is provided but heat insulation is necessary, such as for the protection of accessories and instruments in exposed, normally unoccupied portions of the plane. Therefore, the problem of heat insulation can be disregarded on any plane which is reasonably soundproofed, and this factor should be considered seriously when trying to decide for or against soundproofing.

The thermal value of the soundproofing installation is established by the fact that the latter decreases the transmission losses from the warm cabin to the cold outside, thereby reducing the necessary capacity of the heating plant. This is best illustrated by the following example:

Calculate by how many btu/hr the transmission heat loss through walls and ceiling has been reduced after soundproofing the navigator's compartment of a two-engine bomber as described in section 3.6. Reduction of heat losses through the bulkheads and the floor shall be disregarded.

There are a few more data needed. The cruising speed of the plane shall be assumed as 170 mph, inside temperature as 68° and outside temperature as −20°F. The total area of walls and ceiling is 101 square feet, and the soundproofing materials consist of: "Type A" Seapak, ⅜" thick and "Type Q-1" Seapak, ⅜" thick, separated by a 1" air space. The thermal values of the skin and cover fabric are negligible and shall not be considered.

The heat loss due to transmission is calculated by the formula:

$$H = A \times U \times (t_2 - t_1) \qquad (4)$$

in which:

H = heat loss in btu/hr
A = area in square feet
U = overall heat transfer coefficient, in btu/hr/ft²/°F
$(t_2 - t_1)$ = temperature differential, in °F

U is calculated from the formula:

$$1/U = 1/f_i + 1/f_o + 1/C + x_1/k_1 + x_2/k_2 + \ldots \qquad (5)$$

f_i and f_o are the inside and outside surface heat transfer coefficients, respectively, C the conductance of the air space, x_1 and x_2 the thicknesses of the heat-insulating materials, k_1 and k_2 the heat transfer coefficients for these materials in btu/hr/ft²/°F/inch.

The accurate calculation of the film-transfer coefficients is quite involved. However, the curves in Fig. 44 gave good approximations for the values of these films at various air velocities. Since the velocity of the air inside the cabin is practically zero, $f_i = 1.65$. f_o, at 170 mph, equals 42.

Solving the above equation first for the compartment without soundproofing:

$$1/U = 1/f_i + 1/f_o = 1/1.65 + 1/42$$
$$U = 1.59$$

and:

$$H = 101 \times 1.59 \times 88 = 14{,}100 \text{ btu/hr}$$

Now, this calculation is repeated after adding the factors for the soundproofing materials. C for a 1" air space is approximately 1.10 (see Chapter XII). The heat conductivities for "Type A" and "Type Q-1" Seapak are the same, namely, $k = 0.264$ btu/hr/ft²/°F/inch. Thus, for x_1 and x_2 equalling ⅜":

$$1/U = 1/1.65 + 1/42 + 1/1.10 + 1/0.264 \times \tfrac{3}{8} + 1/0.264 \times \tfrac{3}{8}$$
$$1/U = 2.5$$

and

$$U = 0.4$$

Therefore:

$$H = 101 \times 0.4 \times 88 = 3560 \text{ btu/hr}$$

Consequently, a saving of 14,100 − 3560 = 10,540 btu/hr or, roughly, 10 stu has been obtained by soundproofing this compartment alone. If these calculations were carried through for all of the other soundproofed portions of the plane, it would be found that the saving will amount to from 30,000 to 40,000 btu/hr by which the rated capacity of the heating plant for this airplane could be reduced.

The question might come up as to how these savings can be calculated, if the soundproofing installation is to be designed for meeting noise levels rather than weight specifications. In this case, calculations cannot be started until after the nonsoundproofed airplane has been test-flown in order to measure noise intensities and predominant frequencies. Obviously, the heating and ventilating group would not care to wait that long before calculating its own equipment.

The answer to this problem is very simple. Although the soundproofing engineer does not yet know the exact materials and thicknesses which he will use after obtaining the flight-test data, he knows approximately what method of treatment he will have to employ for various sections. Therefore, he can very well approximate the heat conductances of all sections, and it will be found, after obtaining the final values for the installation, that the approximation was a closer one than is common in the calculation of heat losses.

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XX

SEATING AND RESTING

1.0 INTRODUCTION

Physical discomfort, whether it affects the ear, eye or body itself, always costs more than it saves. Discomfort which is caused or aggravated by flying in an airplane keeps paying passengers away and may ruin an otherwise well-managed airline. If the airplane is a military one, discomfort can handicap its occupants to such an extent that they may fail in their mission, with subsequent loss of both plane and crew. These are the considerations which make proper facilities for seating and resting a comfort feature of prime importance.

2.0 SEATING

Riding for some length of time in even the most comfortable automobile or train seat will cause fatigue and, finally, cramps and actual pain. Brief stops and walks are the best and simplest relief. But for air travel there is only one solution: design of a seat more comfortable than any existing one. Such a seat must meet innumerable requirements to make it suitable for use on an airplane, straining the ingenuity of the engineer to the utmost and creating an industry.

2.1 GENERAL REQUIREMENTS. Warren McArthur, one of the pioneers in this field, summarizes the requirements of airplane seating by stating that provisions must be made for the variation of the human form and man fatigue, when confined in sitting position for long periods of time, and that this must be achieved by simultaneously considering (a) heavy load under gravitational stresses, (b) severe weight restrictions, (c) maximum comfort, and (d) many mechanical movements and adjustments. These adjustments are for variation in the size of the occupant as well as for changes of the seating position.[1]

In addition to these general requirements there are those which concern the specific needs of the occupant who may be a pilot, radio operator, gunner, stewardess or passenger. Obviously, it would be impossible to build a standard airplane seat which would fit every condition equally well. For this reason, there must be numerous types of chairs designed in such a manner as to attain a particular purpose and this purpose only at optimum weight and efficiency.

Chairs can be generally classified as military and non-military. (Seating facilities for crews of airliners are so similar to those of military planes that they can be considered in the same group.)

2.2 MILITARY SEATS must not only provide physical comfort but also assist in the task of their occupants. Facilities for resting in the seat are merely an added feature. Considering the severe conditions imposed by military flying, such as gravitational forces strong enough to cause black-outs, enemy fire, long watches without any rest, particularly severe weight and space limitations and many others, it is not surprising that the design of a military chair entails more and greater problems than that of the non-military variety.

2.21 *Requirements.* The military flier may be confined to his seat for many hours during which he must efficiently perform strenuous mental labor, yet retain his full alertness lest he jeopardize his plane and the lives of his comrades. Consequently, his seat should provide all such features which give him useful rest and, in addition, facilitate the physical labor required for his job. This necessitates numerous adjustments for lowering or raising the seat, moving it fore or aft, turning it on a swivel, reclining the back and others. These adjustments must be accomplished by few and simple controls, with individual or combined locking mechanisms in easy reach of the occupant.

Access to the seat must be such as to permit rapid movement into or out of the seat, in spite of adjacent obstructions. Structural difficulties often induce the designer to make exceptions to this rule which can have serious consequences. The outcome of a combat may hinge on the speed with which a crew member can get into his seat, or a life may depend on the ease with which a wounded flier can be lifted out of his chair. Even during normal operations, stumbling or involuntary aerobatics can result in great damage. The author remembers an incident when he attempted to squeeze out of the co-pilot's seat of a bomber and knocked the throttle of the starboard engine wide open.

The military chair must be strong enough to support and hold an occupant even during the most critical flight evolutions such as dives and sharp banks at high speeds. Corrosion, wear and vibration are by no means minor problems. Under certain conditions, provisions must be made for the attachment of protective armor. Finally, all of this must be achieved at the eternal "another five pounds less."

As Mr. McArthur points out, the chair manufacturer does not have all of the answers, and only close cooperation between him and the fuselage designer can result in a satisfactory solution. Therefore, the airplane manufacturer should furnish complete information regarding type and purpose of the desired seat, the kind of load which it must withstand, the space available for it, obstructions, the overall dimensions allowable and, preferably, a schematic diagram of the chair showing the desired movements.

2.22 *Location.* In addition to the proper selection of the best seat, it is highly advisable to consult the chair manufacturer in locating it. A poorly chosen location can obviate many of the ingenious features of a seat. On the other hand, if no better location is available, a different selection or special design may be needed.

Most difficult and important are the design and location of seats for pilot and co-pilot. Both the Army and Navy have specified the relationship between the positions of the seat, control wheel and pedals. In order to meet these specifications, the seats must be adjustable for occupants of different size. At the same time, it should be possible to tilt the back so that the pilot can rest when not operating the plane. All controls must be within easy reach and all of the essential instruments must be in full view. Furthermore, the occupant should have access to maps, writing utensils and similar necessities. Finally, the movements of the occupant and chair must, in no way, interfere with the maze of controls, switchboards and similar mechanisms with which the average cockpit is filled.

Somewhat more freedom is allowed in locating chairs or seats for the rest of the crew. Usually, it is feasible to place navigator, radio operator and flight engineer sufficiently close to each other to avoid the necessity for conversing by means of the inter-phone, yet far enough apart that their work zones do not overlap.

There are, of course, no given rules for such arrangements since size and purpose of the airplane are the main factors in choosing the best suitable location for individual stations. Once the approximate location has been determined, the selected chair should be so mounted that its occupant can quickly and easily get in or out, is within easy reach of and full vision over the equipment with which he has to work and is in arm's reach of shelves or drawers which contain often-needed utensils. The relationship between a drawer and seat must not entail difficulties in opening or closing the former.

Locating military chairs from the standpoint of protection during combat will be discussed in a later chapter. Placing a mock-up or, better still, a final model of the chair into the mock-up of the airplane is usually the best way to ascertain whether the selected chair and location serve their purpose.

2.23 *Load.* Quoting McArthur again, specifications for loading requirements usually consist of a seat load applied downward, a safety-belt load applied forward and upward at varying angles, and a back load applied either horizontally or perpendicularly over the back on some specified area. Less frequently given are side loads which are mostly required on swivelling chairs and on chairs mounted sideways in the airplane. According to the same reference, military planes must take up to 2400 lb load on the seat, 1600 lb on the safety belt and 1200 lb on the back.

Loading tests are made with 50 lb bags of lead shot which are applied by gravity while the chair is being suspended at various angles.

2.24 *Construction.* The great loads to which an airplane chair is subjected and the subsequently required flexibility result in very complex stresses. Therefore, the chair frames are made from tubular members of high-grade aluminum alloys which are reinforced by steel bracing. Anodizing and cadmium-plating, respectively, are applied throughout as protection against corrosion.

Cushions must be elastic and spring back to their original shape when the chair is unoccupied. They are made of special, flame-proofed and wear-resistant materials and must be easily removable. Both seat and back of the chair are so shaped as to form "pans" for seat-back or back-pack types of parachutes. The acoustical value of the upholstery in providing sound-absorption is incidental but should not be overlooked.

Often, the chair must run on tracks so that it can be slid back in order to permit the occupant to get in or out of it; in some cases, space limitations are so severe that the chair must be foldable to attain this purpose. Since such constructions are not only very difficult to design and build but are heavier and less efficient, the designer of the fuselage should try to avoid the need for them.

A pilot seat of the reclining-back type for long-range airplanes is shown in Fig. 134 which illustrates the Warren McArthur Model No. 225. The following describes it:

> The seat is mounted on tracks 9″ center to center, sliding fore and aft in the airplane. The height of the seat is adjustable in fifteen positions from 11″ to 17⅜″ above the floor line. The seat and back adjust simultaneously through 5 positions. There are removable cushions and provisions for seat and back parachutes, a removable head rest and hinged "Bantamite" arm rests. Rubber elevation straps lift the seat to its up position. Armor plate may be fastened to the back and sides. The seat and back pans are formed "Bantamite" to take either seat or back type parachutes respectively.

This seat is tested under the following loads: 2400 lb down-load on seat; 1200 lb down-load on back with back horizontal; 1600 lb belt-load with belt at 40° to track; 1000 lb belt load with belt parallel to back; 700 lb up-load on harness fitting parallel to back; 600 lb forward-load over top of back on take-up mechanism; 400 lb down-load on both arm rests; 50 lb side-load on both arm rests.

It is obvious that only most ingenious design achieved all of the above features at the almost unbelievably low weight of 33.87 lb for the complete chair, including upholstery. Another example of design is the radio operator's chair (Fig. 135), Warren McArthur model No. 163. The following specifications are given:

> The seat is mounted on tracks allowing movement forward and backward, controlled by a hand-operated lock. It has a swivel base with 8 locking positions in 360 degrees, also controlled by a hand-operated lock. The seat is fitted with seat and back pans to accommodate standard parachutes when seat and back cushions are not in use. Weight upholstered is 19.5 lbs. Loads tested: Seat load 1200 lbs., belt load 1600 lbs., back load 600 lbs.

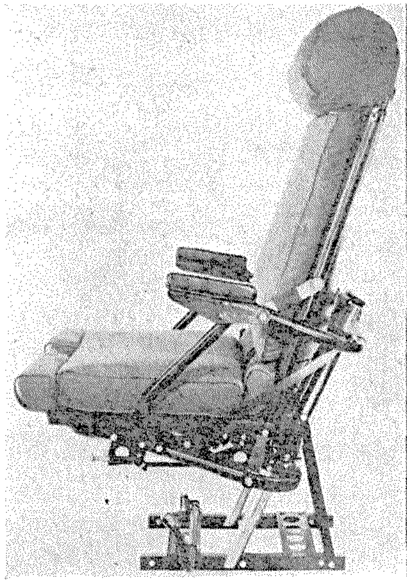

Fig. 134

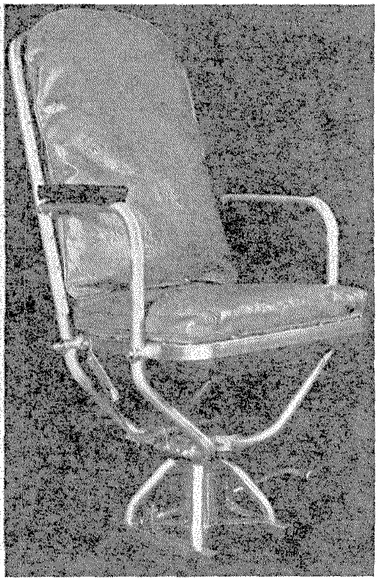

Fig. 135

2.25 *Special Designs.* The great variety of tasks which the military airplane and its crew must perform have resulted in many suggestions and special designs. Most of these designs endeavor to adapt a chair to emergencies arising from military operations such as the one which proposes to assist in the prevention of black-outs during dive-bombing. In this scheme, the seat is flexible and automatically assists the pilot into a supine position as he pulls his plane out of the dive. As soon as the bomb is released, control of the aircraft passes to a gyroscope unit.[2]

"Parachute Chairs" and similar combinations of aircraft seats and parachutes will be described in a following chapter.

2.3 NON-MILITARY SEATS. As indicated before, the chair for a commercial airliner or private plane is somewhat easier to design than the military seat although its features must provide more than mere elimination of discomfort, even up to the point of luxury. However, weight and space limitations, while still far greater than for ground conveyances, are relaxed and adjustments are considerably less complex than those needed by military crews. On the other hand, there are some requirements which are added so as to provide mutually profitable comfort.

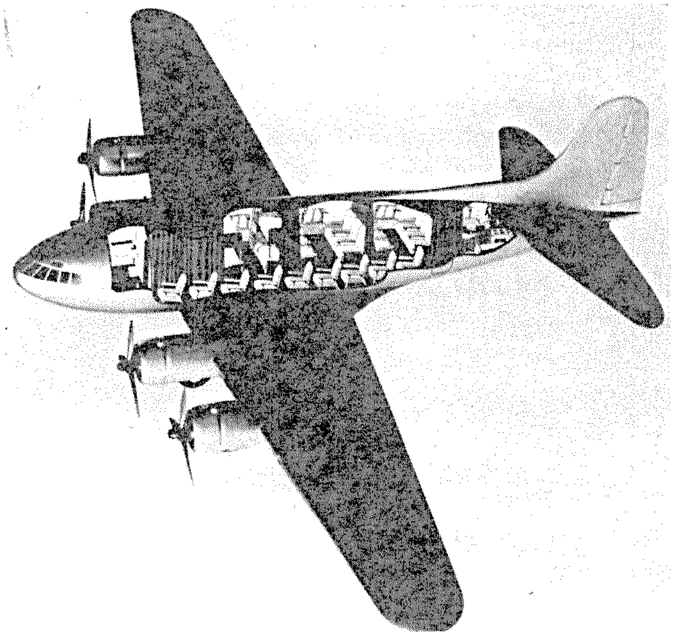

Fig. 136

2.31 *Requirements.* The chair in a non-military plane must be able to support even very heavy passengers under all conditions of private and commercial flying, including bumpy air and rough landings. It must be adjustable to occupants of different size and be so comfortable as to minimize sitting fatigue even over very long periods of time. It must have a reclining back so that the passenger can change his position or rest. The latter is particularly important when sleeper service on airlines is restricted, confining passengers to their seats for as long as 17 hours.

Under normal circumstances, the chair on a long-range transport must be converted easily into a rigid and comfortable bed which entails mechanical problems. Artistic appearance must be given the closest attention so that styling and appointments of the cabin match.

2.32 *Location* of seats in a private plane of the cockpit or cabin type is usually determined by the same considerations which apply to a military flight deck: comfort while handling the controls or a maximum of comfort within a minimum of space.

Chairs in commercial transports can be located in two ways, either by laying out the most desirable arrangement of seats and compartments, and then building the fuselage around them, or by placing seats as well as possible in an existing fuselage design. Naturally, the former is preferable.

A perfect example of the first method is illustrated in the cut-away view of a Boeing 307-B Stratoliner such as used by TWA for transcontinental passenger service before the War (Fig. 136). The fuselage is 74 feet long and 11½ feet in diameter, providing ample room for 33 passengers. Besides the control cabin the Stratoliner has spacious kitchen and pantry, double and triple compartments, comfortable single seats and roomy berths. Provision of sufficient leg room in compartments is one of the prime factors in determining the arrangement of seats. Figure 137 shows a view of one of the triple compartments on the Stratoliner. It is evident that passengers, although sitting opposite each other, can readily stretch out and rest in comfort without disturbing each other. Such comfort can be attained only by very shrewd utilization of every available fraction of an inch and the functional design of the fuselage. The roominess of the compartment is further accentuated by its unique styling, designed by Howard Ketcham, famous stylist of airplane cabins.

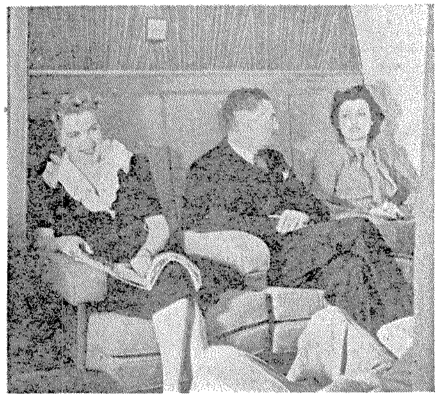

Fig. 137

The second method of locating seating accommodations in an existing fuselage is of particular importance for the anticipated conversion of bombers and military transports into post-war airliners. The economy of space and the presence of obstructing and unsightly structural members in the cabin makes it appear that such a task can never be fulfilled without many unsatisfactory compromises. The best proof that perfect conversion, no matter how difficult, can be achieved by good engineering is the job which the then Vought-Sikorsky Division of United Aircraft did shortly before the war in converting one of its four-engine Navy bombers into a luxurious transatlantic passenger plane. A number of these airliners are now operated by American Export Airlines in successful transatlantic service. Figure 138 shows a compartment in one of these Flying Aces which scarcely resembles a military airplane.

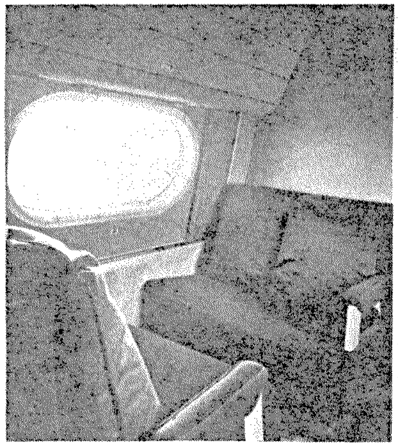

Fig. 138

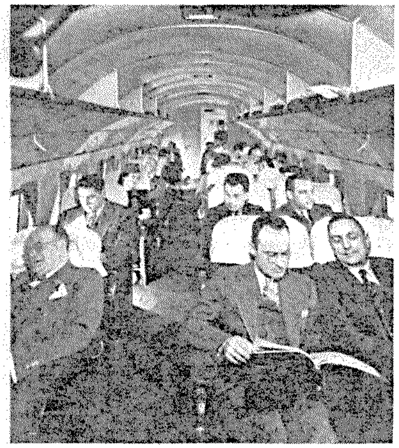

Fig. 139

The seats are 40″ wide and adjustable to two positions. The frames are built into the plane so that they are integral structural members and yet, so light that they add a negligible weight. Two pillows are at the back of the seat. The Pullman-type upper berth is so designed as to leave ample headroom and fit into the artistic scheme of the cabin.

Other considerations in locating passenger chairs are, proximity to ashtrays, call buttons, individual air-supply inlets and light switches. Good location with respect to the window, ceiling lights, heating and ventilating openings are of equal importance. Avoidance of drafts, hot-air blasts, stratification and foul-air pockets near or around seats cannot be overemphasized. Finally, passenger compartments should be as far aft as possible in order to simplify the task of soundproofing.

If sleeper service is not required, a seating arrangement as shown

in Fig. 139 is the most popular and economical. The seats in this United Air Lines Mainliner have a double fingertip control, permitting easy adjustment of seat and back without disturbing passengers fore or aft. Such conveniences as individual air-supply nozzle, stewardess call button and others are within reach of every passenger. Movement in and out of seats is unimpeded. Special brackets permit quick attachment of tables. Cushioning of these chairs is so complete that even long rides cause hardly any fatigue.

2.33 *Load.* Inasmuch as the flight maneuvers of a commercial plane are less abrupt than those of a military one, load requirements are somewhat less. They range upward from 1000 lb load for the seat, 1000 lb load for the safety belt and 300 lb load on the seat back at shoulder height.

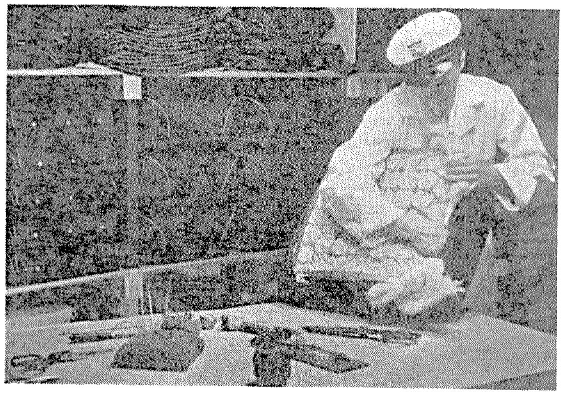

Fig. 140

2.34 *Construction.* The principles of construction employed in the design of a passenger chair are very similar to those of military planes; structural details are established by identical methods of stress analysis.

Special attention must be given to the cushions which take most of the wear yet are one of the main factors affecting the general appearance of the chair. A deep permanent *set* which is unavoidable after lengthy use, is neither sightly nor conducive to comfort. For this reason, airlines maintain upholstery shops in which they constantly restore their supply of cushions (Fig. 140).

3.0 Resting

To most people the main advantage of airplane travel lies in the saving of time over travel on the ground. However, much of this saving is obviated unless passengers can arrive at their destination fully rested. This requires resting accommodations which give the opportunity for normal sleep and, at the same time, are suitable for use on aircraft.

While a comfortable chair with reclining back is a good place for a snooze, it can not take the place of a regular bed or berth. Yet, there is even less room for a conventional bed on an airplane than there is on a train, so it has been necessary to adapt the scheme of a seat-bed combination to the peculiar conditions existing on an airplane. The ensuing problems are, of necessity, quite involved.

3.1 REQUIREMENTS. The airplane berth must be able to take loads similar to those on the chair. Often it is composed of the same units but in a different arrangement. The change-over from chair to bed and vice versa must be extremely simple and rapid, and not require physical effort or special tools. Bedding must be light and flameproof, yet serve its purpose. The size of the bed should be equal to or greater than that of a similar berth on a train and accommodate even large and heavy people without discomfort.

Joints must be strong enough to prevent collapsing of either berth or chair under high gravitational stresses and be such as to avoid rattling or vibration. Once resting accommodations are provided, limitations of weight or space should never be permitted to reduce this comfort below the minimum required for restful sleep.

3.2 LOCATION of the berth is determined by the location of the chair from which it has been converted. Thus a convertible chair should never be located from the standpoint of seating comfort alone.

One of the major problems is the need for proper and draftless circulation of warm air through both upper and lower berths. Consequently, all of the engineers concerned must get together and decide on the best possible location of berths and methods of ventilation. Close cooperation is also needed in placing individual air nozzles, call buttons and reading lights. Passengers must be able to step in or out of beds easily without hazard. For this reason, it is always advisable to put a number of adjacent and opposing chairs into the mock-up and have several people try them both as seats and berths.

3.3 CONSTRUCTION. The change-over from chair to berth can be accomplished in a number of ways. The Pullman arrangement for the upper berth is usually the simplest one. In the previously mentioned Fig. 138 the opposing seats in the cabin of a "Flying Ace" form the lower berth while the upper folds down in Pullman fashion. Both berths are 6′ 6″ long and up to 40″ wide, thus providing a comfortable double bed.

Spacing is such that the occupant of the lower berth has enough headroom to sit up.

A similar arrangement is shown in Fig. 141 which illustrates the type of berth provided by United Air Lines on their sleeper planes, prior to the war. This berth is 6′ 5″ long and wider than a twin bed.

A good view of another simple yet sturdy method of erecting and bracing upper and lower berths is given in Fig. 142 which shows a section in one of Boeing's famous 314 Clippers. Operated by Pan American in trans-oceanic service, these giant flying boats provide the latest in travelling luxury for 89 passengers and, if needed, up to 40 berths like the ones shown in Fig. 142.

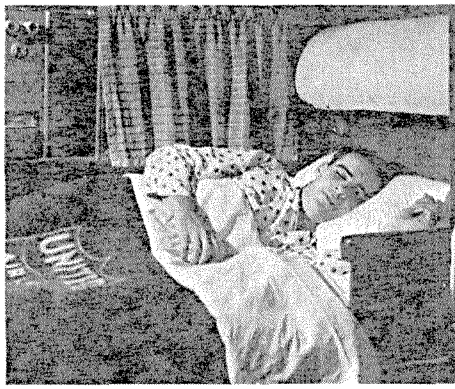

Fig. 141

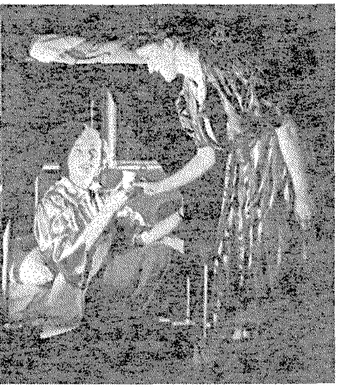

Fig. 142

It can be expected that, after the war, airplane berths will be further developed to match the near-perfection of present-day airplane seating.

3.4 BUNKS. The design of bunks for the crews of military or commercial airplanes appears quite simple, consisting merely of a frame of aluminum alloy tubing with steel reinforcements, and canvas or a similar material stretched over this. Yet, a well-built bunk requires as much consideration as a seat or chair. It must be properly stress-analyzed and constructed to hold up under all conditions of military flying. It must be located in a suitable and not too noisy place, keep its occupant from being thrown against the metal skin or floor of the plane during abrupt flight evolutions and, before all, give enough resting comfort to justify its existence.

The design of bunks and stretchers for wounded in emergency or regular ambulance planes covers a field in itself which is so specialized that its discussion would go far beyond the scope of this text. Still, the fundamental requirement for airplane bunks, seats and berths, whether military or non-military, always remains the same; first, consider the minimum comfort necessary in each specific case and then the limitations of weight and space.

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XXI

LIGHTING

1.0 INTRODUCTION

One of the major contributors to comfort and yet still in need of much improvement is the lighting and illumination in modern aircraft. Both too much and too little light cause eye strain and fatigue, and result in headaches, thus contributing as much to the general level of discomfort as noise or cold or an uncomfortable chair.

Proper lighting on aircraft should be given the closest attention and taken care of by engineers who are familiar with this subject. Some of its aspects will be discussed below.

2.0 SPECIFICATIONS

Lighting requirements for aircraft are, in many cases, specified in such generous terms as "adequate illumination shall be . . ." or "sufficient light must be . . ." and even "reasonable lighting should be. . . ." Obviously, the interpretation of what is adequate, sufficient and reasonable can vary from zero to infinity, with subsequent dissatisfaction to all.

The writer of the general specifications for an airplane cannot be expected to be an expert in hydraulics, structural design and illumination but he must know enough about all of these to provide those men who are the experts with sufficient information to give him exactly what he wants.

In order to explain, for instance, what his concept of "reasonable lighting" is, the specification writer need not be familiar with the rather complex science of illumination. However, it is necessary for him to be able to express the lighting requirements in non-ambiguous units and figures. One of the main stumbling blocks in this respect is the definition of *lumen, candlepower* and *foot-candle.*

The *candlepower* is a unit of light quantity, based on the International Candle. Thus, if a light bulb is said to have a candlepower of 10, it means that its intensity is ten times greater than that of the International Candle.

The *lumen* is the "unit of luminous flux" or, the amount of light emitted by a point source of one candlepower through one unit solid angle. Since there are 4π such angles in a sphere, it can be said that one candlepower is the source of and equal to 4π lumens.

The *foot-candle* is the unit of illumination and equals one lumen/sq ft. In other words, if an area of one square foot receives a luminous flux of one lumen, it is said to have an illumination of one foot-candle. This can be written as:

$$L = F \times A \tag{1}$$

in which L is the amount of lumens, F the number of foot-candles and A the illuminated area in square feet.

Since the illumination decreases as the square of the distance from the light source, the second fundamental equation becomes:

$$F = \frac{C}{R^2} \tag{2}$$

in which F is the number of foot-candles, C the candlepower of the light source and R the distance of the light source from the area to be illuminated, in feet.[1]

Now, if the writer of the general specifications for an airplane defines the desired illumination of, for instance, a radio-operator's table in foot-candles, it is easy to calculate the candlepower of the light source, mounted at a given distance from the table, which is necessary to obtain the specified illumination.

In reality, these calculations are a little more involved since it must be determined what percentage of the light emitted by the lamp is actually utilized. This depends on reflectors, lenses and other factors and is called the "coefficient of utilization."[2]

The total illumination of a room such as an airplane cabin depends also, largely, on the amount of light which is being reflected from the walls, ceiling, floors and other objects within the cabin. The coefficient of reflection, that is, the ratio of reflected light to incident light, varies greatly for different materials and colors. Polished and white surfaces reflect a great deal of light while rough and dark surfaces absorb most of it. Consequently, both weight and current for light sources can be saved by keeping the interior of the cabin as light as possible although darker colors may often be more desirable for a particular artistic scheme.

The simplest and quickest method to ascertain whether the illumination meets the specifications throughout the various stations of an airplane is by means of photo-voltaic or photo-electric light meters which measure the amount of light received through an opening of given area in foot-candles. Meters of this type are widely used by photographers.

3.0 MILITARY LIGHTING

One of the most vital assets of a flier is good eyesight. Since the eyes of military flight personnel are usually subjected to greater and more continuous strain than any other part or organ of their body, optical comfort equipment is of the utmost importance.

A variety of factors contributes to the burden placed on the eyes of military fliers. Foremost is the need of their sharp and strained use for long periods of time. Scanning the glaring sky, often against the sun, for enemy aircraft; examining the ground through clouds and haze; observing many instruments over a wide angle; reading fine script and figures in insufficient light; lengthy use of optical instruments and night flying, all play havoc with the eyes of even the healthiest person.

Because of the importance of preserving the unrestricted eyesight of military flight crews, optical comfort has been of great concern to aeronautical medicine. Concentrated research has finally evolved three distinct phases of sight control, namely an appropriate program of pre-induction testing, sight conditioning and sight protection.

3.1 PRE-INDUCTION TESTING. In testing the eyes of applicants for military flight duty, it has been necessary to develop and standardize methods which are quite different from those used for any other purpose. Good eyesight alone is not sufficient. Much of the military flying is done at night and under black-out conditions so excellent night vision is a prerequisite. Under low brightness, colors are often not recognized and only the rod system of the retina is effective in seeing.[3] Objects appear larger and dimmer against their background, more to some people than to others. Thus, it is necessary to examine applicants under all conditions of military flying, so as to arrive at acceptance levels which can be attained by a good average yet meet the stringent requirements of military flying.

3.2 SIGHT CONDITIONING has contributed greatly to increased efficiency of flight crews. This has been accomplished by determining the factors which affect their vision, and either developing methods to train and condition eyesight for such circumstances or by recommending means to improve them. The following factors have been found to require attention: conditioning for night-flying, effect of anoxemia, effect of large gravitational forces, effect of exhaust gases, unsuitable design of optical equipment and insufficient illumination.

Acuteness of vision at night varies considerably with the individual, however, it can be generally improved by correct diet with stress on Vitamin A, exercise of the eye muscles, blindfold drills, night look-out technique and similar training. For the normal individual, rod response will increase up to 100,000 times as the eyes are kept protected from light for a period of at least half an hour. This adaptation will be completely lost by looking into a strong light, even for a short time. As a result, it has been necessary for pilots, leaving the brightly illuminated "ready room," to adapt their eyes to the darkness of the night sky for a lengthy period before the take-off. Several schemes have been worked out, and used with encouraging success, which tend to eliminate or shorten this dangerous period. Apart from the conditioning training, described above, dark goggles have been developed which are worn for some time before the night take-off. A more recent development is a plastic polaroid goggle which has been perfected by the medical-research section of the Bureau of Aeronautics. These goggles employ a combination of lenses and filters which allows practically no light to stimulate the portion of the retina used in night vision. By using the dark-adapter goggles the pilot can remain under full illumination, work out his flight plan and take off with his eyes sufficiently adapted to fly without difficulty.

Anoxemia or lack of oxygen at high altitudes has been proven to decrease the visual accuracy in dim light and narrow the field of vision. Latent defects become apparent and exaggerated, and night vision is decreased. This is an added reason to stress the need for proper use of oxygen, even at medium altitudes. There remains the harmful effect of exhaust gases upon the eyes. Inasmuch as these gases are highly toxic, proper design of exhaust and ventilating systems is doubly imperative.

The effects of extraordinary gravitational forces show themselves, among others, by increasing the reaction time of the flier. This is more evident in vertical than in horizontal acceleration. No information has been found as to whether this can be overcome by some method of training. Since these accelerations are an integral phase of military flying, it appears that their consequences must be taken into account as unavoidable.

3.3 SIGHT PROTECTION. While the foregoing phases of sight control belong mainly in the realm of the flight physician, sight protection is the task of the comfortization engineer which he can solve satisfactorily only by close cooperation with the physician and other design groups. This concerns, specifically, the design of optical aids or equipment, and interior lighting.

3.31 *Optical Equipment.* One of the basic prerequisites for sight protection in cockpit-type planes is the provision of suitable goggles, which must be selected for maximum efficiency and minimum inconvenience. Since their main purpose is to keep harmful drafts out of the eyes, they must fit snugly, yet avoid pinching and resulting headaches. The lenses must neither unreasonably absorb nor in any way distort light but, if needed, reduce glare. The field of vision must be such as to permit full movement of the eyes without moving the head. It is also advantageous to coordinate the design of the goggles with that of helmet, oxygen mask and microphone.[4]

Of equal importance is the construction of the windshield which must be designed for maximum vision and minimum air resistance. Of course, as Mario di Giovanni[5] points out, vision alone cannot dictate the design of an airplane. Although the line of vision should preferably be normal to the windshield in order to minimize refraction, it is necessary to shape it in such a manner as to obtain the least possible drag which, usually, results in a V-type windshield. However, despite dictates of aerodynamic design, windshields must give the pilot all of the necessary vision, particularly during landing. Violation of this rule is a definite hazard, not only while landing but also during action.

Giovanni suggests that the distance between pilot and windshield should not exceed 26″ to 32″ since this will give a maximum field of vision, and small specks of dust and other matter are less visible at shorter distances.

The location, angle and size of portholes and windows must be so selected that they serve their purpose without undue strain on the eyes and body of the crew members who are stationed near them for look-out and similar purposes. This is also true for design and installation of the optical accessories of a military airplane, such as sights, navigation instruments and related equipment.

The eye strain caused by looking through optical instruments with fine hairlines and need of frequent correction is unavoidable. However, the instrument should be so designed as to place the operator in the most comfortable position and prevent neck and back strain. Eyepieces should be provided with viewing attachments and properly cushioned to prevent injury to the eye during abrupt motions of the plane. The design of adjustments must take into account that the operator may have to wear heavy gloves.

3.32 *Illumination.* Large window areas increase the weight of an airplane and aggravate the task of sound- and heatproofing. For this reason, the normal tendency is to keep the number and size of windows to a minimum. But a window is not only to look out of but to admit sufficient light and thus avoid too large a consumption of electric current during daylight hours. If, for structural or military reasons, the window area is limited below the requirements of adequate illumination, artificial light sources must be installed wherever necessary.

Efficient illumination is required by the navigator for instance; on his work may depend the fate of plane and crew; the radio operator should have sufficient light to observe, operate and service his equipment properly; and crew members whose duties include the accurate reading of important instruments must have good light.

Narrow cat-walks should have enough light to eliminate hazards. A minimum illumination of 1 foot-candle should be specified for unoccupied areas which are used for transit; 2 foot-candles should be the minimum in occupied areas where only moderate discrimination of detail is essential; and not less than 5 foot-candles should be provided at the navigator's table and wherever discrimination of fine detail is required.

Unfortunately, the interior illumination of many military airplanes is still inadequate. It is usually furnished by small bulbs in reflectors which are arbitrarily distributed throughout the cabin and often mounted on adjustable arms, giving a concentrated but still insufficient amount of light. The reason for this deficiency is by no means lack of existing equipment but rather the frequent failure of appreciating the urgent need for better and more light. This can be improved by definite specifications for the number of foot-candles required at various stations, by carefully selecting the best location for the light sources, by the use of more adequate light fixtures, by development of suitable fluorescent lamps and choice of paints and finishes of optimum reflecting power.

Therefore, a closer study of lighting requirements will yield the greatest possible economy and attain the desired result at a minimum of current consumption. It will also find simple means to keep the light strictly within the cabin so that it will not leak to the outside nor into the flight deck or to persons who must work in the dark.

Special attention must be given to the optical problems of the flight deck. The multitude of flight instruments demands such wide disposition that, even in daylight, their observation is difficult. Simplification and better coordinated arrangement of instruments is the logical answer to this problem and has long been the subject of diligent research.

The problems of adequate sight in the flight deck are multiplied many times at night. As mentioned before, improved night vision can be obtained through a number of means. However, the best adaptation is completely destroyed by the bright flashes of guns or tracer ammunition so that the outcome of a night combat depends mostly on which pilot sees the other one first.

Of course, piloting and navigation at night can be easily accomplished by a trained crew through use of blind-flying instruments. On the other hand, the instruments are of no use unless they can be plainly seen. Instrument illumination must offer sufficient contrast to distinguish the pointers and dials without effort, yet not so much as to affect the vision of the pilot to the outside. This is splendidly illustrated in Fig. 143 which shows a night view through the windshield of an airliner as seen by the pilot.

Illumination of instruments can be accomplished in several ways, namely by dashboard or reflecting lighting, ring lighting around the instrument, radium-coating and fluorescent lighting. In the latter method dial and pointers are coated with a paint which fluoresces brightly under ultra-violet light. This light is supplied by a special bulb which is placed between a reflector and a "black-light" filter. If the filter is removed, the lamp provides visible light for emergencies.

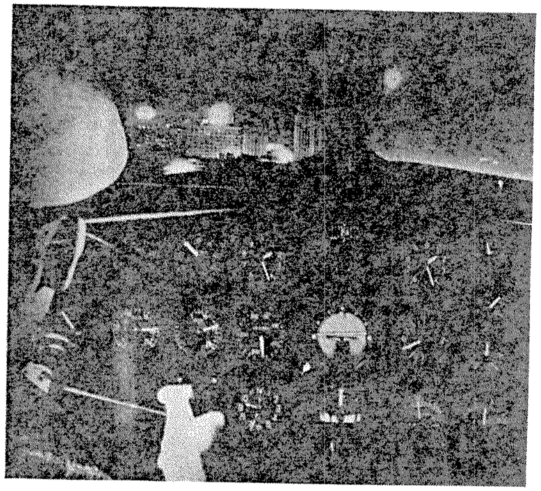

Fig. 143

4.0 Non-Military Lighting

Much that has been said about lighting on military airplanes applies equally to commercial airliners. Their crews have tasks similar to those aboard military planes, and their lighting requirements can usually be met in an identical manner.

The following additions concern, in particular, the illumination of the passenger cabin.

4.1 DAYLIGHT FLIGHTS. In the absence of military considerations, the passenger of an airliner expects a window area large enough to afford a good and convenient view of the scenery below and also to provide sufficient light. Sufficient light permits reading normally without undue eye strain at all seats, even those towards the center of the cabin. Eastern Air Lines furnished the picture shown in Fig. 144 which proves that the light for the center-seat passengers furnishes enough illumination in the cabins of their airliners to take snapshots. An illumination of 5 foot-candles and up, at shoulder height, is generally considered to be adequate.

Insufficient illumination is not the only source of visual discomfort. Too much illumination or glare is often actually painful. Glare in the cabin is usually caused by sunlight which is reflected from the wings and into the eyes of the passengers.[6] Painting of the upper surfaces of the wing is not feasible since this would add too much weight. Shades and curtains are used at present to eliminate glare at the discretion of the passenger. However, much research is being conducted in the development of non-glare materials and blinds.

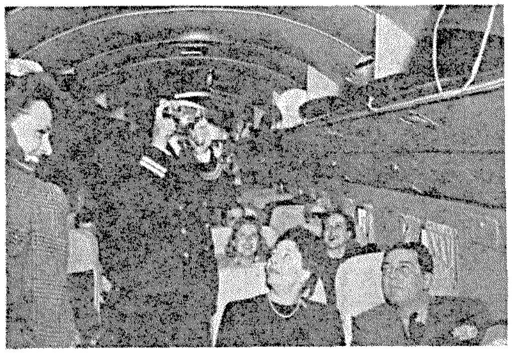

Fig. 144

4.2 NIGHT FLIGHTS. Illumination of a passenger cabin at night presents several unique problems. The interior as a whole can be illuminated easily by dome lights, and quite efficiently if the following rules are observed: The number and distribution of dome lights should not be established arbitrarily but by calculation of the lumens necessary to obtain 5 candlepower at every chair. The globes must be selected for good light transmission and low glare, and preferably be made from translucent plastics. The loss of light by dust on reflectors and globe must be taken into account in calculating candlepower. Colors within the cabin must be selected for best reflecting power, notwithstanding different wishes of the stylist. This is of particular importance if the cabin lighting is indirect.

During the latter part of the night, some of the passengers wish to rest while others prefer to continue reading. In order to satisfy both, the dome lights must be dimmed or turned off entirely and individual reading lights provided. In doing so, it is necessary to furnish enough light for the reading passenger without disturbing a neighbor who wants to rest. This is accomplished by means of concentrated beams of light which are produced by a small bulb and lens, set deep into the cabin wall. As a result, the light source itself is not visible and a disc of light is projected toward the passenger, just large enough to cover a magazine or book. Although this keeps most of the light from adjacent passengers, there is enough reflection from the white paper to inconvenience others. Further research in this respect is indicated.

Illumination of berths is accomplished in a similar manner. The curtains used on aircraft berths are of special, lightweight and flameproofed materials which are highly opaque so that a resting passenger may use his light without embarrassment to himself or inconvenience to others (Fig. 145).

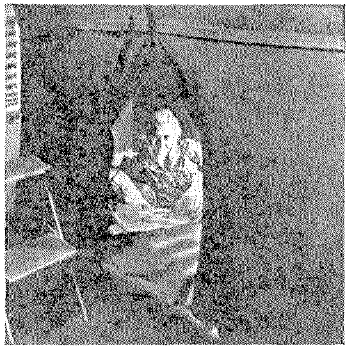

Fig. 145

5.0 LIGHTING EQUIPMENT

The low voltage furnished on airplanes requires high amperage for their electrical equipment in order to obtain the desired wattages. In addition, vibration and other stresses are higher than normal for ground applications. Consequently, it was necessary to develop an entire line of special light bulbs for use on aircraft. The General Electric and Westinghouse Companies have now made it possible for designers to select a production bulb to meet any one of their many requirements. Similarly, switches, conduits, junction boxes and other electric equipment are now available which are designed and manufactured in accordance with all Army, Navy and commercial specifications for aircraft.

Specialization of electric aircraft equipment has gone so far as to combine electrical comfort devices with others in order to save space and weight. An example of such a device is the combination of air diffusers with dome lights discussed previously. The newest development along this line is shown in Figs. 146, 147, and 148 which illustrate an overhead anemostat for airplane cabins, with integral dome light and translucent globe, manufactured by the Anemostat Corporation of America.

It is quite significant that manufacturers are now spending a considerable amount of time and effort for the development of aircraft comfort accessories. Before the war, the small quantities involved and the then unusually strict specifications discouraged the research in and manufacture of such specialized accessories. This pertained particularly to electric equipment, including motors, relays and lighting fixtures for aircraft which were most difficult to obtain. The growing interest of existing manufacturers and creation of entire new industries promise rapid improvement of those features which are still more or less adaptations from designs for the ground.

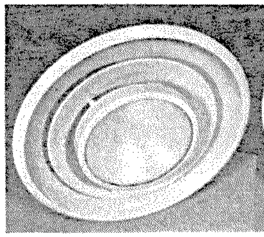
Fig. 146

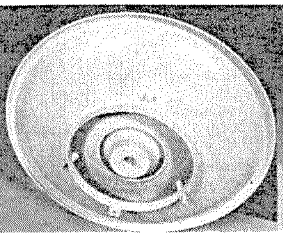
Fig. 147

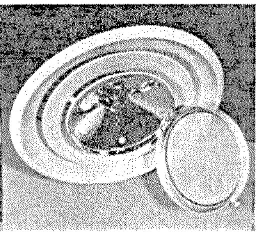
Fig. 148

Aircraft lighting should profit very much from this trend and be given many added facilities as, for instance, radically new methods of illumination, lighter and better fixtures and fluorescent lighting throughout. The latter should become standard with the unavoidable change-over to higher voltages and alternating current.

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XXII

FIGHTING COMFORT

1.0 Introduction

The purpose of *fighting comfort* is threefold, namely to assist the military flier during aerial combat and thus make him more efficient; next, to help him overcome the effects and after-effects of combat and, thereby, protect him from becoming defenseless; and finally, to save his life in emergencies and, with it, the valuable investment which his government has made in his training.

Consequently, *fighting comfort* may be said to consist of the three general classes of *combat, protective* and *emergency* comfort.

2.0 Combat Comfort

Combat comfort is attained, not so much by special devices or equipment, as by design considerations which take into account the physical requirements and limitations of the human body. While this appears self-evident, it is surprising how often this important rule is violated.

Thus, movable guns should be so constructed as to require a minimum of effort for operation and to avoid cramped position of the gunner. Guns, lookout ports and sights should be positioned for best possible vision and a minimum of physical strain, particularly on head and eyes.

Handles exposed to cold should be protected by rubber or similar material to prevent freezing the hands, and gunners must be protected from exposure to strong drafts and intense cold during combat. Sights should be constructed to accommodate the normal eye and permit lengthy sighting without causing headaches and eye fatigue.

All stations must be readily accessible and permit rapid relief of a wounded crew member. Clothing should be selected in such a manner as to afford the desired protection and service, without impeding motion of arms and legs.

All of these are simple rules, but their neglect may result in the loss of valuable aircraft and their crews.

3.0 Protective Comfort

This, also, is largely a matter of proper plane design. Its first phase concerns such an arrangement of seats, stools and stations in general as to protect the flight crew as well as possible against direct hits and bullet splatter.

This can be achieved by keeping the necessary exposure to a minimum and by placing personnel behind protecting equipment. Unfortunately, this is not always feasible. The gunners, for instance, can be given only partial protection against bullets coming from the direction in which they are firing; otherwise their vision is obstructed. Similarly, the pilot requires vision towards the front, sides and ceiling, so that his head must remain almost fully exposed.

This brings up the questions as to whether armor plate and how much of it should be provided on a military airplane. In spite of remarkable developments which have greatly reduced the weight of armoring and, at the same time, increased its protective properties, the weight is still considerable if the armor is to be at all worthwhile. On the other hand, it must be reasoned that every crew member is vital to the purpose of the airplane or he would not be on it. Therefore, injury to or death of any one of the flight crew seriously affects the effectiveness of the airplane. A satisfactory compromise between the scope of a comfort feature and its weight is again necessary.

The armoring of a plane also serves as a protection for not only the crew but also for pipe lines, control cables, wiring and other vital equipment, and thus reduces the vulnerability of the plane. Sound judgment in the selection of armor has resulted in a very great superiority of American over Japanese aircraft although the former was heavier and often less maneuverable than the latter.

In a complete analysis of this complex subject,[1] Horace J. Alter points out that protective armoring must consider the angles at and from which bullets might strike the plane, and how much of the airplane structure and equipment they would have to penetrate before reaching a crew member at his battle station. In some cases, it may be sufficient to provide heavy aluminum alloy sheets or even splatter shields. In other cases, heavy armor is needed to protect as much of the body as possible without interfering with the task of the individual. Alter states that, if the plate is placed close to a person, its area can be reduced to about 8 sq ft. Personnel operating movable guns should be covered by flexibly mounted plates which require less area than fixed ones and give protection in the direction of fire.

The fire protection of pilots in single-seaters is particularly difficult. The engine covers the front, but sides and back are usually more vulnerable than in larger planes. Therefore, it is necessary to provide armor plate for the pilot's seat and legs. Face and chest can be protected by bullet-resistant glass in the windshield.

Another phase of protective comfort concerns the physical limitations of man when flying at speeds approaching that of sound and the effects of the ensuing accelerations. Although detailed data may not be published, it is common knowledge that the gravitational forces encountered when banking or diving at high speeds are many times the normal gravitational force, g. The effect on human beings varies somewhat with the individual but, as these forces—expressed as multiples of g—exceed 4 g, an excessive amount of blood is forced into or out of the brain, resulting in serious disturbances and, finally, unconsciousness or "black-out." Even at moderate accelerations, hearing and vision is affected; increasingly so as the black-out condition is approached, which is quite common in the *pull-out* during dive-bombing. Normally, all functions are quickly restored as the acceleration diminishes or stops. However, there are numerous cases in which fliers recovered too late to prevent disaster.[2]

Much has been written about this phenomenon, and medical science has contributed valuable devices and suggestions for delaying or shortening the black-out period, and facilitating recovery. A seat which forces the pilot into a supine position was described in a previous chapter. There are several schemes for automatically taking the controls from the pilot in dive-bombing the moment he releases the bomb; tight bandages serve to impede excessive movement of blood from one part of the body to the other, and cold air blasts into the face of the pilot are helpful.

Undoubtedly, extremely interesting data will be released after the war, to assist in making flight at high speeds safe and comfortable in postwar commercial aircraft.

4.0 Emergency Comfort

Once the combat is over, it is usually necessary to make a number of urgent repairs to plane and crew alike. The purpose of the former is to keep the plane flying and get it back to its base or a friendly field for regular and thorough repair. Of still greater importance, however, are the lives of the crew and it is necessary to provide not only very complete first aid facilities but, if the plane must be abandoned, means for safe return to the ground and home. This entails a great variety of methods, schemes and devices which fall into the class of *emergency comfort*. They comprise: design for emergency, first-aid equipment, fire-fighting equipment, parachutes and life rafts.

4.1 DESIGN FOR EMERGENCY concerns, primarily, means to put previously-described, essential comfort features back into operation after they have been damaged by enemy fire. This applies to accessories for rapid repair or replacement of oxygen equipment, plugging of holes in the skin of a supercharged plane and the like. The ventilating system must be able to take care of toxic gases which might leak into the cockpit or cabin from a shattered engine manifold. The heating system must be so designed and located as to permit emergency repairs and not become a source of danger itself, if struck by a bullet.

Cots and bunks must be suitable for giving utmost comfort to a wounded flier and facilitate first-aid work, such as blood infusions. There also should be at least one hatch in every cabin or compartment type of airplane through which a wounded flier can be lifted to the ground with a minimum of effort and pain.

4.2 FIRST AID. Because there may be need of major surgery immediately after combat flight crews must be well trained in major first aid; and the selection and design of equipment which permits such operations on a military airplane and by inexperienced personnel is likewise highly important. Means for sterilization, pain relief, blood infusion and the like should be available. Selection and regular inspection of these accessories by flight physicians is urgently recommended.

Even more difficult to compile is proper first-aid equipment for pilots of cockpit-type planes who may have to dress major injuries unassisted, while continuing to control their plane. This calls for design of ingenious devices, for instance, bandages or tourniquets which can be applied single-handed.

Although not intended for dressing combat wounds, the contents of the Woods Emergency Type First-Aid Kit, as provided by American Airlines, are typical for first-aid equipment needed on aircraft:

1 Esmarch Triangular Bandage
6 3 x 4 Picric Acid Gauze Pads
1 Large Bandage Compress
2 1-yard pkgs. Absorbent Gauze
1 1-ounce Absorbent Cotton
3 Gauze Bandages, 2 in. x 6 yds.
1 Gauze Bandage, 1 in. x 6 yds.
2 Cotton Roller Bandages, 2 in. x 5 yds.
1 Adhesive Plaster, ½ in. x 5 yds.
1 Bottle Aromatic Spirits of Ammonia
1 Burn Ointment
1 Tourniquet
1 Pair of Scissors
1 Pair of Tweezers
1 First Aid Book
1 Applicator Bottle Alcoholic Solution of Iodine
1 Box Band-Aids

4.3 FIRE-FIGHTING EQUIPMENT. Fire aboard a plane as anywhere may be caused by many things. And the close proximity of the powerplants, large gasoline tanks and fumes make even stricter precautions necessary, apart from the fact that a fire aloft is much more difficult to fight and considerably more dangerous than on the ground. Conditions are even more stringent for the military airplane. It is exposed to attack by an enemy who will try every means at his disposal to set the plane on fire and thus put it out of combat. Fire-fighting is difficult because every crew member is needed and the source of fire is usually not easy to reach. An emergency landing may mean loss of plane and crew. Thus, the utmost perfection and simplification in fire-fighting equipment has long been the concern of military authorities.

Invaluable contributions in this respect have been made by Walter Kidde and Company who have developed the equipment shown in the following figures and which is used successfully on both military and commercial airplanes. The method uses carbon dioxide gas under high pressure. Expanding to 450 times its stored volume, the carbon dioxide extinguishes the flame by cutting off its oxygen supply. One of the main advantages of this method lies in the fact that, after the fire has been extinguished, there is no trace of the gas left and no damage done beyond that caused by the fire, as would be the case with the use of water and some chemicals.

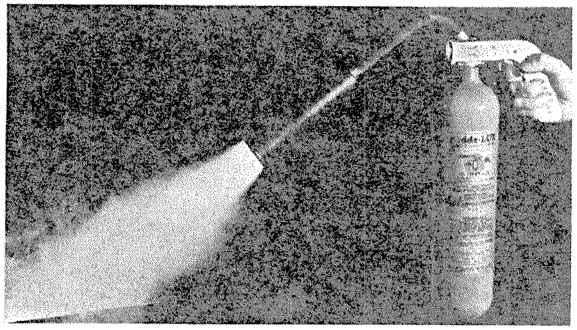

Fig. 149

Fire-fighting with this method can be accomplished in two ways: by means of the portable extinguisher and by the built-in system or *remote control.* Figure 149 shows the portable extinguisher which consists of a steel cylinder, containing two or more pounds of the gas under a pressure of 850 psi at 70°. The valve is operated by a trigger, and the gas is discharged through a nozzle toward the base of the flame. The portable unit is kept accessible in areas where fire is liable to break out. Figure 150 shows a section of the Pan American Clipper in which the extinguisher is located within a maze of wiring and cables. A cat walk gives the required accessibility.

The built-in system is used to protect the engine accessory compartment where most airplane fires originate, due to the great flammability of aviation fuel. It operates on the same principle as the portable unit but differs from it in that the gas cylinder is located outside the fire zone. The gas is distributed through a piping system which is so designed as to discharge the gas at the points where the hazard is known to exist. The release valve is operated by a control on the instrument panel within easy reach of the pilot. Figure 151 shows the control box (lower foreground) in a multimotored plane. This control is equipped with directional valves which permit discharge of the carbon dioxide into the burning engine space from the storage cylinder, indicated by arrow. The action of the discharge is illustrated in Fig. 152.

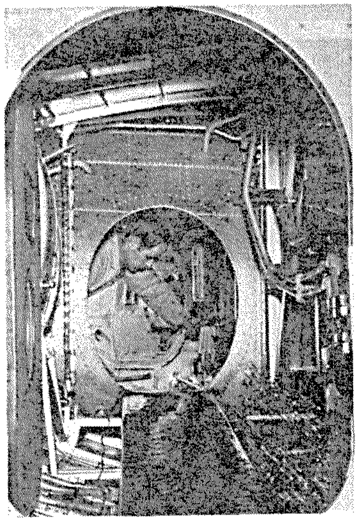

Fig. 150

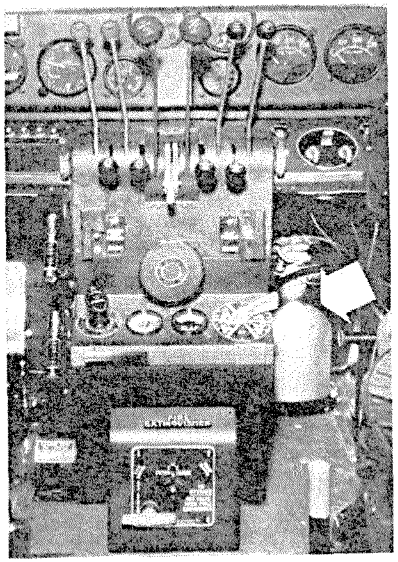

Fig. 151

As a further feature of this system, engineers of Walter Kidde and Company developed an ingenious device: the *impact switch*. This switch contains a trigger mechanism set to go off under the impact of a crash. In this case, the trigger automatically discharges several pounds of liquid carbon dioxide into the engine compartment thus preventing fire and explosions, if the pilot is unconscious or incapable of quick action.

Bottled carbon dioxide has numerous other uses on aircraft, some of which will be described shortly.

4.40 PARACHUTES. The percentage of fliers who have had to "hit the silk" and were injured or killed as a result of the jump, although following all instructions, is extremely small. To achieve such safety in what once was a daredevil stunt took many years of methodical development and engineering. The present-day parachute is an intricate piece of mechanism which must be designed, built, used and maintained with the utmost care because, once resort to it becomes necessary, it is the only thing between life and death.

Fliers saved by a parachute will, without hesitation, proclaim it the number one comfort feature. To the engineer and serviceman parachutes offer interesting aspects, so that everyone connected with aircraft should have at least a general concept of the problems connected with them. The use of parachutes, their rigging and maintenance require diligent study and practical experience but the data presented below, compiled from information supplied by the Switlik and Pioneer Parachute Companies, should serve as a brief introduction.

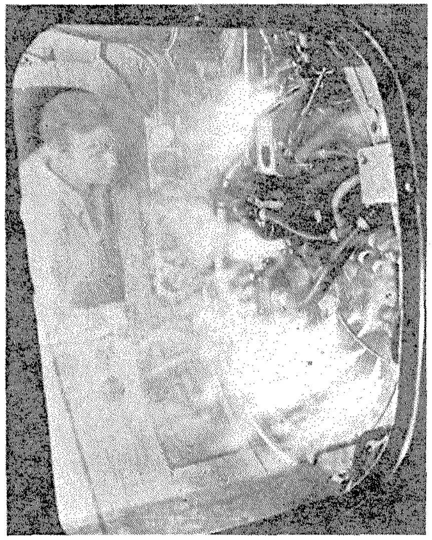

Fig. 152

4.41 *Construction of the Parachute*—A parachute consists, essentially, of five assemblies; the Pilot Chute, the Rip Cord, Pack, Harness and Canopy. The parts are shown in Fig. 153, which illustrates a Switlik Safety Chute. The following is quoted from its description:

> A pull on the rip cord handle "A" releases the single pin fastener "B," freeing cable "C" from around pilot chute bead and channelled edge of tray "D." The combination pack cover and pilot chute "E" thus released, is repelled from the pack by the pilot chute springs contained within the pilot chute. The continued pull on the rip cord operates the ejector "F" which is folded under the second fold near the apex "G," throwing the peak of the canopy away from the body into the air stream, preventing blanketing and assuring a positive and rapid opening.

The pilot chute in the Switlik parachute serves both as a means to assure the opening of the main canopy and as the cover for the packed

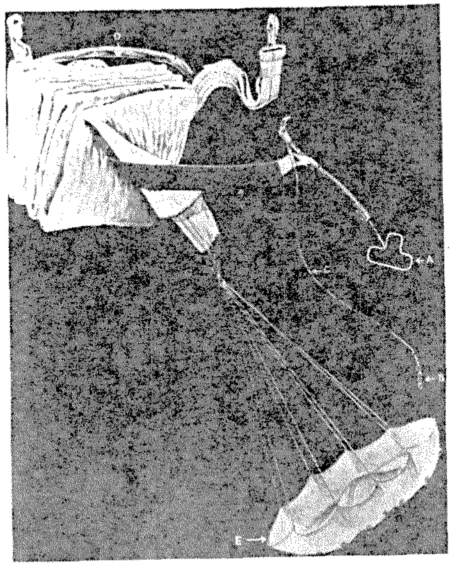

Fig. 153

parachute. It is octagonally shaped and provided with eight lines, each of which has a tensile strength of 100 lb. The pilot chute springs are formed, flat steel and inserted between tape.

The rip cord consists of a handle made of cadmium plated, chrome molybdenum tubing, the stainless steel rip cord cable and necessary fittings made from nickel-steel alloys.

The purpose of the ejector in the Switlik parachute is to prevent slow opening, if the pack faces the air blast during a jump.

The pack tray is 1½″ deep and is made of cadmium-plated wire covered with water-repellent duck. The edge forms a channel for the rip cord.

The harness consists of soft and pliable webbing, with a minimum strength of 3,000 lb. As shown in Fig. 154, it is easily adjustable and holds the body securely without discomfort. The back pad serves to keep the harness in shape, similar to a vest.

The main part of a parachute is, of course, the canopy. It is fabricated by joining 24 or 28 similar trapezoids of high-grade silk to make up a polygon. The diameter of the canopy developed is 24 ft for the regular size and 26 ft for the oversize. The projected sizes are about 18 and 22 ft, respectively. The canopy is provided with a fixed vent. Its suspension lines are continuous from one lift-web link, through the canopy, to the opposite lift-web link. They are made from strong silk and consist of an outer braid and a core.

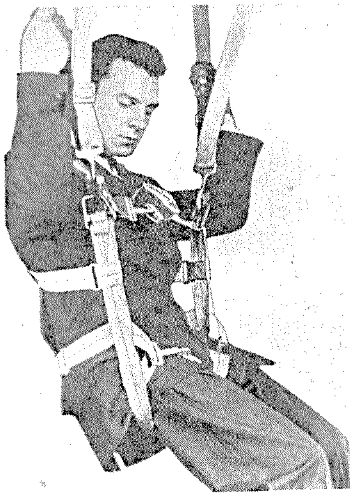

Fig. 154

Constructions and designs vary, of course, for individual manufacturers, however, the general principles follow the above outline. Strict specifications by the Army and Navy have further contributed to standardization of design.

4.42 *Operation of the Parachute*—Originally, there were two methods of leaving an airplane by parachute, namely the *drag off* and the *free fall.* In the former method, the jumper holds on to the plane, lets his parachute open and the wind drag him off into space. This method is almost entirely obsolete now.

The *free fall* is most common in modern parachute jumping. The flier leaves the plane with as little effort as possible, steps into space, as it were, or kicks off with a slight push in order to avoid somersaulting and subsequent delay in the opening of, or damage to, the parachute. When he is sure to have cleared the plane, he pulls the rip cord, thus freeing the pilot chute which, in turn, pulls out the main canopy. Many accidents have happened, if an excited jumper pulled the rip cord too soon and the parachute became fouled in the structure of the airplane.

In addition to the drag off and free fall there are several automatic methods of leaving a military plane which are to facilitate the jump, if the plane should be spinning or is otherwise difficult to leave. Some planes are provided with trap doors which are opened by operating a simple control and permit the pilot to fall into space without the effort of climbing over the cockpit. A somewhat more complicated method consists of a mechanism called the *automatic chair chute.* The occupant is strapped to his chair which combines seat and parachute. If he has to bail out, he pulls a lever which drops the chair with its occupant out and clear of the plane. Such installations have been used on ambulance planes.

Release of the parachute may be either manual or automatic. Automatic release is effected by attaching the rip cord to the airplane. After the jumper has fallen 20 or 30 feet, the parachute is jerked open without action by the jumper. The purpose of this method is to prevent fatal accidents caused by the failure of an unnerved jumper to pull the rip cord. Events have shown that such a precaution is not necessary and the automatic method is mostly confined to testing of parachutes by dummies or mass jumps as performed by paratroops.

As the terminal velocity of a clothed person is about 130 mph, the opening shock, when jumping from planes exceeding this speed, can be reduced by delaying the opening until the body has decreased its speed to that velocity. This, of course, can be done only if there is sufficient altitude.

The minimum advisable altitude for an emergency jump is 200 feet although jumps have been made successfully from lesser altitudes. On the other hand, jumps have been executed from altitudes exceeding 30,000 feet without harm. The low air density and extreme cold at these altitudes make it advisable to delay the jump until lower altitudes are reached. Since the fall of the body will be accelerated until the increasing air resistance prevents further acceleration at what is termed the *terminal speed,* delayed opening of the parachute is not quite as bad as it sounds.

Means for emergency air supply when jumping from great altitudes have been discussed before[3] and should be provided on high-flying craft. Protection of hands, ears and nose is essential since freezing of those parts during jumps from such altitudes has been reported repeatedly.

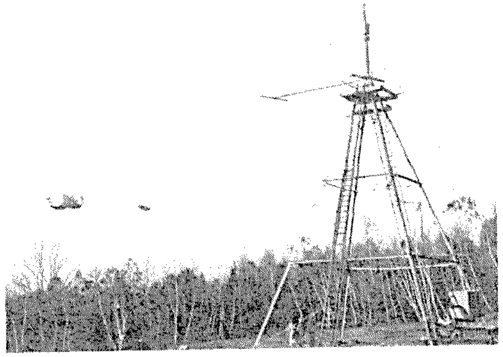

Fig. 155

The chute should open in not more than 2½ seconds after the rip cord has been pulled. This is the average opening time at 70 mph while, at 100 mph, this period is reduced to about half. The open parachute should descend at a rate of 21 fps, if carrying a man weighing 175 lb with equipment.

The parachutist has a certain amount of control of direction by pulling in 2 or 3 feet of several suspension lines on the side toward which drift is desired. This control is limited by two factors, namely the danger of the canopy collapsing and by the subsequent increase in the speed of the fall. As the parachutist approaches the ground, he must observe the wind direction and endeavor to land with his back toward the wind. His legs should be drawn up slightly so as to give him *spring.* The shock of landing is comparable to that experienced when jumping from 12 or 14 feet.

Harness is so designed that the jumper can free himself very rapidly and thus prevent his being dragged over the ground. Experienced jumpers will begin to unfasten the straps a few feet over the ground and hold on to the lines until a second before they land. Special mechanisms have been designed for paratroops to release their harnesses by means of a *quick release button* so that they are ready for action the moment they land.

4.43 *Testing*—Considering the importance of the parachute, it is not surprising that all specifications call for a rigorous testing program. Most of the testing is done by means of dummies of the shape, size and weight of the average flier, which are dropped from a plane under specified conditions. In order to observe the action of all components closely, the Pioneer Parachute Company built the test tower, shown in Fig. 155, on which the dummy is whirled around a circle of 200 ft diameter, at speeds ranging from 70 to 350 mph. A high-speed motion picture camera records every detail of the parachute's operation.

Typical tests as required by the Civil Aeronautics Administration are given below in a chart representing test results of Switlik parachutes.

Tests	*A*	*B*	*C*	*D*
Number of tests required	12	5	3	2
Load	170 lb dummy man	170 lb dummy man	600 lb load strength test	170 lb human
Air Speed	70 m.p.h.	70 m.p.h.	100 m.p.h.	Terminal velocity
How packed	Normal	3 twists in lines	Normal	Normal
Required minimum opening time	3 seconds	4½ seconds		250 ft delayed opening
Switlik 24′ dia. opening time	2.5 seconds	3 seconds		
Switlik opening time (oversize)	2.6 seconds	3.8 seconds		
Maximum rate of descent (permitted)	21. ft/sec	21. ft/sec		21. ft/sec
Switlik rate of descent (24 ft dia.)	16.15 ft/sec	16.5 ft/sec		16.7 ft/sec
Switlik rate of descent (oversize)	15. ft/sec	15.7 ft/sec		15. ft/sec

4.44 *Selection of Parachute*—Special conditions require special designs for optimum efficiency. This applies also to parachutes and has resulted in a number of types for particular applications. Choice of the correct type of parachute contributes greatly to its usefulness and, often, to the success of a jump. The following types are the most common:

Fixed Seat-Pack Parachute is so worn as to serve as seat during flight. It is rigidly attached to the harness. Figures 156 and 157 show front and rear view, respectively, of a flier using a Pioneer parachute of this type. It is worn mainly where chairs are provided with *pans* to accommodate the seat-pack chute and enough head room is available, and where movement of the wearer during flight is not required, as in cockpit-type planes.

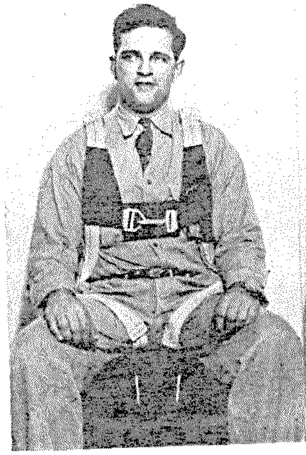
Fig. 156

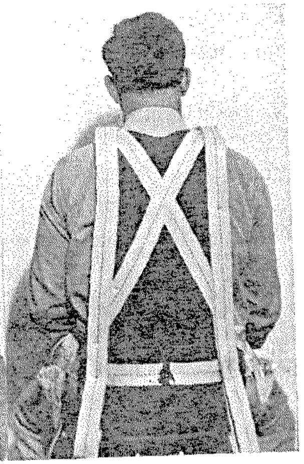
Fig. 157

Detachable Seat-Pack Parachute is quickly detachable and attachable to the harness. It is used in bombers and planes where unimpeded movement through the plane is necessary. The flier wears merely the harness, with the parachute stored in a convenient place. If an emergency arises, the chute is quickly attached to the harness.

Back-Pack Parachute is worn on the back as illustrated in Fig. 158, showing a flier wearing a Switlik parachute of such construction. The 3" thick pack fits closely to the back and lies perfectly flat. It is recommended for special use where head and leg room are limited, or where cabin space is cramped. It can be worn for long flights without inconvenience. Back-pack parachutes may be either of the fixed or detachable type. A model of a fixed Pioneer back-pack chute is shown in Fig. 159.

Chest Parachute is detachable and worn on the chest, usually together with a seat-pack or back-pack chute. It is employed mainly for practice and exhibition jumps as an added safety feature.

Chair Parachute is designed for use in pilot and passenger chairs of cabin-type planes. The parachute forms the upholstery in the chair frame and is covered by fabric which blends in with the cabin interior. The passenger adjusts and attaches the harness as he sits down. If he arises, the pack emerges from the recessed chair back and is ready for use. Two Switlik installations of this kind are shown in Figs. 160 and 161.

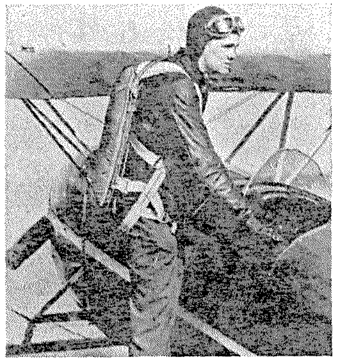
Fig. 158

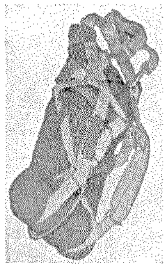
Fig. 159

Airliners are normally not provided with parachutes. Inspection and maintenance of these planes is such that the slight chance of need for parachutes does not justify carrying such equipment. Also, it would be an almost impossible task to make a score of frantic passengers jump safely in an emergency, and the mere presence of these devices with the then necessary instructions in their use before take-off would be disturbing in the atmosphere of utmost safety for which American airlines are famous.

4.45 *Maintenance*—A parachute must be examined regularly to ascertain whether it is still suited for its vital purpose. According to federal regulations, it must be inspected and repacked every 60 days. The following factors are of importance:

Holes and tears in the canopy should be carefully investigated. If smaller than 2″, they may be darned. Tears larger than 2″ but smaller than 12″ should be patched. Holes larger than that require replacement of the panel.

A parachute may never be packed while it is damp or wet. If it has come in contact with salt water, it must be rinsed in fresh water and allowed to dry for 48 hours. The chute must be checked for brittle silk, worn webbing, broken stitching and similar damage. Metal parts must be examined for rust and wear, and replaced, if necessary. A parachute may be used repeatedly, if it is well taken care of but, if there is any doubt as to its condition, it should be returned to the factory and submitted to a drop test.

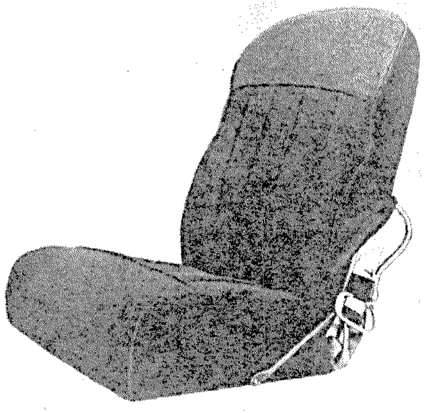

Fig. 160

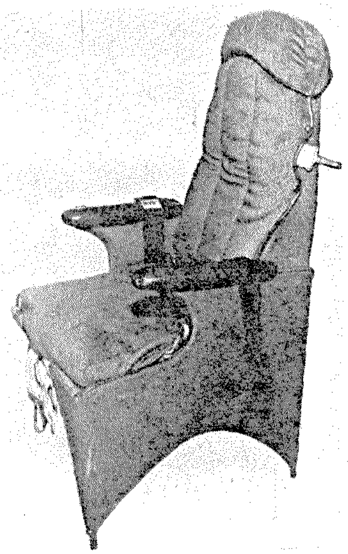

Fig. 161

Packing of parachutes is such a complex and important operation that it should be left to a licensed parachute rigger.

5.0 Life Rafts

War knows no sentimentality. A military flier is given a parachute not merely to save his life but also to keep the services of a trained and experienced soldier. Therefore, it is not enough to have him return safely to the ground from his disabled plane. It is equally important to get him back to his base.

If the parachutist lands on friendly territory he normally has little difficulty in rejoining his unit. If he bails out over enemy territory, his chances of avoiding capture and returning are practically zero. Between these two extremes is a third possibility: he may land where not men but nature throws difficulties into his way. Provision of emergency rations, tools and similar equipment will facilitate this task, if he lands in wild and uninhabited country.

Warfare both in the Pacific and around Europe has added another ruthless enemy for the parachutist—the open sea. A great number of fliers parachuted to safety over the ocean only to perish in the waves. As a result, it was necessary to furnish fliers whose missions took them over great stretches of open water with devices which would greatly improve their chances for return. This required means to keep them from drowning when hitting the water; means to keep them afloat for a lengthy period and, at the same time, protect them from sharks, sun, thirst and hunger; and finally, means to attract help.

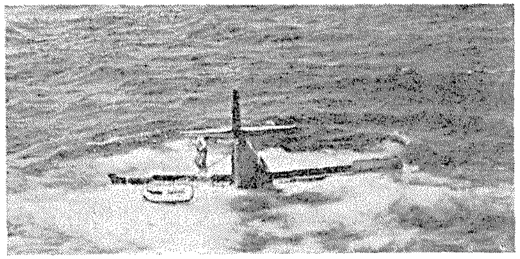

Fig. 162

The simplest device is an ordinary life belt which has not proven to be of much service. Next is the collapsible life raft. These rafts or boats are made from rubber and carry from one to seven persons. They are inflated by means of carbon dioxide and provided with tarpaulins, oars, repair kit, hand pump, water cans, "K" rations, knife, whistle, first aid kit, fishing utensils and other equipment needed for a lengthy stay on the water.

Since it often happens that a landplane sinks before the occupants have a chance to remove the boat and inflate it, Walter Kidde and Company developed a system which uses their water-sensitive switch

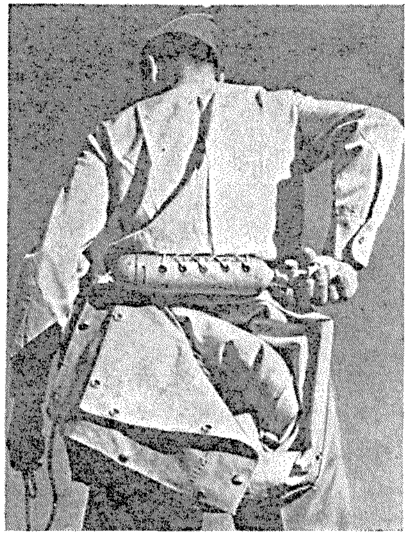

Fig. 163

and two cylinders containing carbon dioxide. As the plane hits the water, the switch opens the release valves on the cylinders. The gas from the first cylinder opens the hatches of the raft compartment in the top of the fuselage. Gas from the second one inflates the raft which then floats free and is held to the plane by a light line. The second cylinder stays with the raft.[4] In this manner, pilots who are forced down at sea find a completely-equipped, fully-inflated boat waiting for them and can climb into it before their plane sinks. Figure 162 shows rescue of a carrier-based pilot by means of this device.

In case pilots have to bail out rather than go down with their plane, they may use the *pack raft* which was also developed by Walter Kidde. Uninflated, this pack raft is no larger than an ordinary briefcase and, like his parachute, is worn by the airman at all times. As seen in Fig. 163, an attached cylinder, about 10″ long and 2″ in diameter, contains compressed carbon dioxide. The control valve is released by the flier as

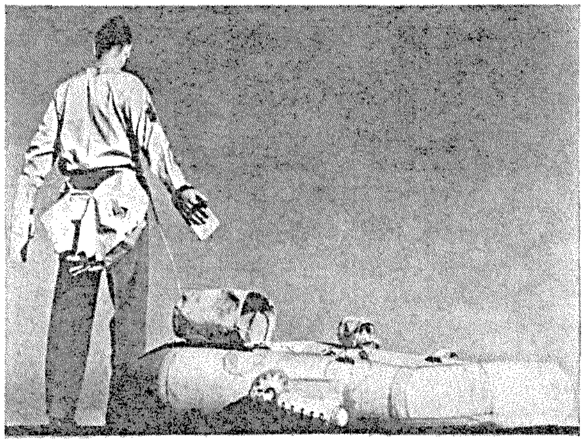

Fig. 164

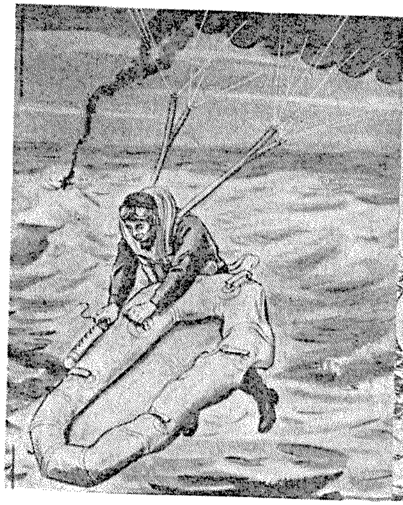

Fig. 165

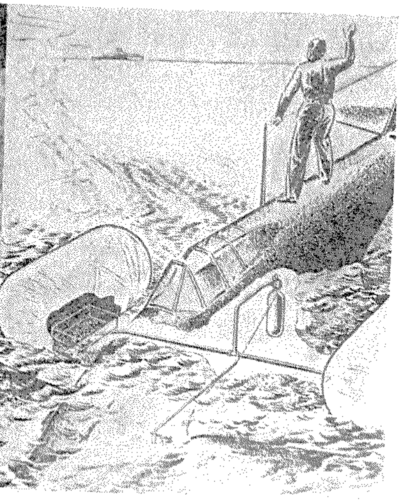

Fig. 166-A

he dangles from the shrouds of his parachute. When he lands on the water, he has a fully inflated rubber boat attached to his body, containing emergency rations, repair kit, sea anchor and paddling mitts (Figs. 164 and 165).

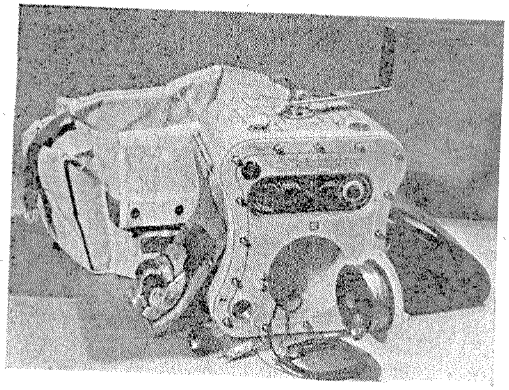

Fig. 166-B

In another application of the water-sensitive switch, the Kidde engineers developed flotation bags or *airplane water wings*. The bags are carried folded within the wings. As the plane hits the water, the switch opens the valves of the carbon dioxide container and the inflated bags pop from their compartment. Figure 166-A shows a pilot awaiting rescue while the bags keep his plane afloat.

One of the latest additions to life raft equipment is the emergency radio transmitter built by Bendix Aviation Ltd.[5] This device weighs only 33 lb and sends out an SOS signal automatically through operation of a hand crank, and is said to cover an area of 100,000 miles. For those who know the Morse code, a keying device permits sending of regular messages. A collapsible kite and hydrogen balloon serve for holding the antenna which should be raised to about 300 feet for best operation. Hydrogen for the balloon is created by immersing a simple generator in the sea water. The entire equipment is packed in a buoyant, bright yellow water-resistant bag. The pack contains the transmitter, kite, two deflated balloons in sealed cans, two spare reels of antenna wire and signal light. Instructions and Morse alphabet are printed on top of the transmitter (Fig. 166-B).

Recent, further developments include devices for day and night navigation which can be used with practically no experience; electric signal lamps which are powered by small, hand-cranked generators and are visible over 60 nautical miles; dye markers which, if sprinkled on the water, color a large area around the raft a bright, emerald green; chemicals which remove the salt from seawater and make it drinkable; and many others which are constantly being augmented and improved.

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[3] Alvin V. Heller, "Bail-Out Bottle," *Western Flying*, June 1942.

[4] "Ejecting a Fully Inflated Raft," *Aero Digest*, April 1943.

[5] "Emergency Radio Transmitter," *Aero Digest*, July 1943.

XXIII

COMPARTMENT COMFORT

1.0 INTRODUCTION

Compartment comfort comprises those features which distinguish the compartment-type airplane from the cabin and cockpit-types. It consists, essentially, of facilities for the serving or preparation of food, lavatory facilities and "ease of motion." While these comforts are common to both military and commercial compartment planes, the airliners incorporate the added features of "comfort of air travel," styling and entertainment. The first three items should be classed as essential comfort as emphasized by the fact that they are required on military aircraft. Their scope varies, of course, with the size and purpose of the plane and may range from the lower limits of essential equipment on war planes to lavish luxury on trans-Atlantic airliners. The last three features fall into the class of luxury only as far as the passenger of a commercial transport is concerned. To the operators of the airline, this comfort is a matter of sound business, therefore, an essential factor in drawing up the specifications for their ships. The same reasoning applies in styling the cabins of small, private planes.

There are no rules or formulas for the provision of compartment comfort. Its type and scope depends on how much it is worth, in terms of weight, to the operator, whether it is a military agency or an airline. Once the maximum permissible weight has been determined, it is the combined task of designers, artists and executives to make the best possible use of it. Considerations of space and price are, often, additional limiting factors.

It is an almost hopeless task to go into the details of each of the comforts mentioned above without encroaching on subjects, entirely alien to aircraft. On the other hand, the story of aircraft comfortization would not be complete without a general description of these features. Many of their technical details have been discussed throughout this text. Therefore, the old Chinese advice that one picture is worth one thousand words will be heeded, and compartment comfort explained by photographs of existing installations supplied by airlines and accessory manufacturers.

2.0 ESSENTIAL COMFORT

Essential, compartment comfort may be defined as equipment or provisions the lack of which would be felt as a distinct discomfort during lengthy trips on military or commercial airplanes of the compartment type.

2.1 FOOD SUPPLY. Facilities for food supply or *catering*, as it is termed on airliners, must be provided for trips exceeding two hours duration. Although the normal time between meals is from four to six hours, inactivity, fresh air and travelling as such tends to make people more hungry than usual. Accordingly, it is necessary to furnish not only regular meals but also in-between snacks, refreshments, and cold or warm drinks.

This problem is simplified on the military plane inasmuch as selection of simple but tasty and wholesome menus is made on the ground without regard for individual preferences, and necessary refreshments included. In addition, flight crews are usually composed of not more than from five to ten members.

On the commercial airliner, passengers may number from a score to several times that many who expect a variety of food to suit their taste or physical requirements. For this reason, the distinction between *food supply* and *catering* is not merely a choice of words.

There are two general methods of providing meals. In the first one, complete meals, warm drinks, etc. are prepared on the ground and stored aboard in insulated containers which keep the food warm or cold. In the other method, there are more or less elaborate cooking facilities on the plane permitting the preparation of a variety of warm foods, from coffee to complete meals.

On military cabin planes, the first method is almost universal. Thermos containers with coffee and ice water are standard equipment. Sandwiches, fruit, candy and cigarettes are supplied mainly on long trips. Emergency rations are always aboard, anticipating emergency landings or the need for parachuting. Permission to smoke within the cabin during regular flight may sometimes be an effective stimulant and nerve tonic. Ashtrays and cigarette lighters should not be considered a luxury but necessary.

Military compartment-type planes usually contain a small galley and facilities for storing food so that warm and fresh food may be available even during very long flights. In addition, a compartment-type plane may have to serve as living quarters for its crew. Cooking facilities are preferably provided by electric hot plates which are simple and safe. Storage compartments are well heat-insulated and, in some cases, refrigerated.

Commercial airlines serve full-course meals three times a day at the usual meal hours. On trans-continental flights with regular stops after not more than four hours, it is the rule to prepare the food on the ground as this eliminates the need for cooking facilities and extra help aboard, and can provide a limited but well-planned choice. Since meals are served shortly after take-offs, the food is hardly off the stove when it reaches the passenger. It is cooked in elaborate kitchens (Fig. 167) which are located at all major airports, and stored either ready to

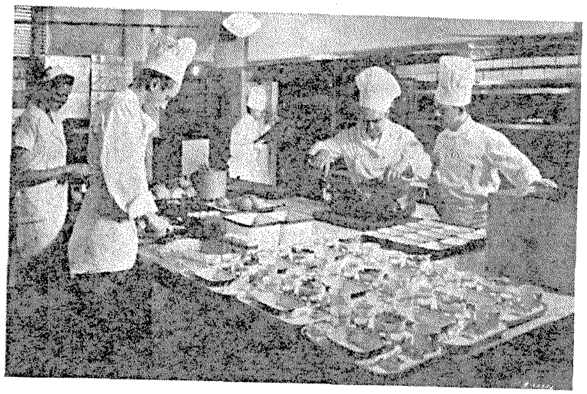

Fig. 167

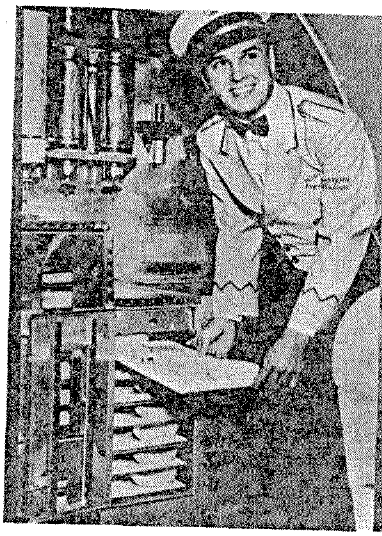

Fig. 168

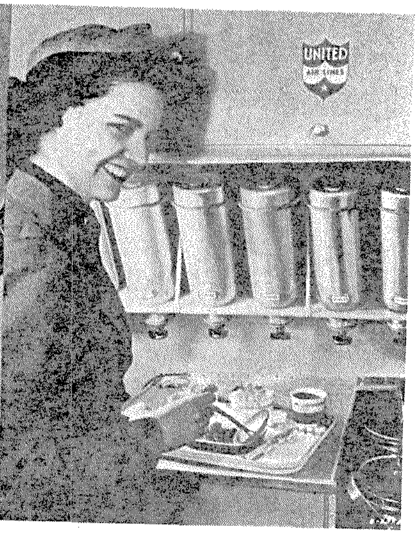

Fig. 168-A

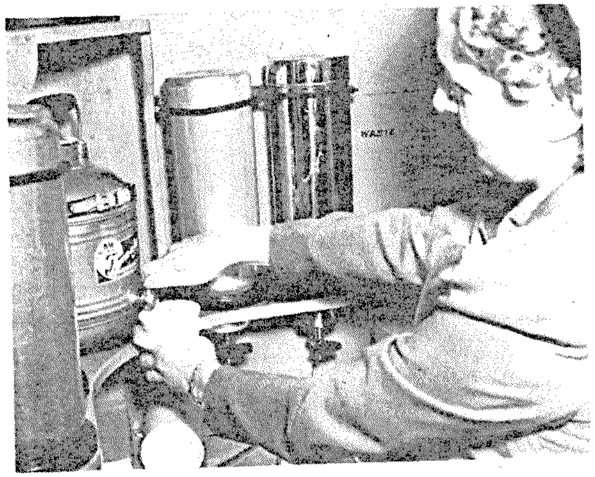

Fig. 169

serve, tray and all (Fig. 168), or dished out during flight (Fig. 168-A). Refreshments between meals are served at all times, at the wish of the passenger. This requires suitable and convenient thermos containers for coffee, icewater, lemonade and milk (Fig. 169).

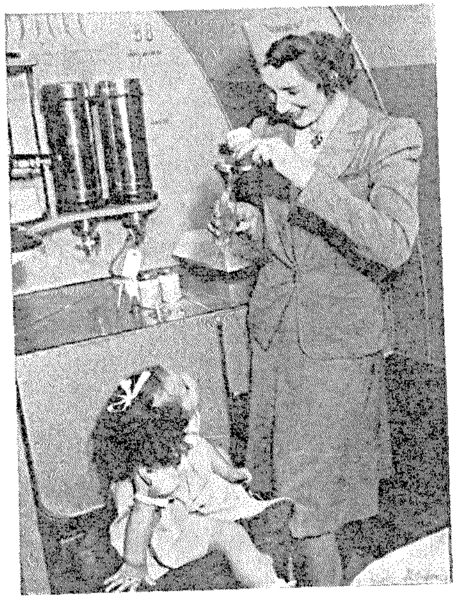

Fig. 170

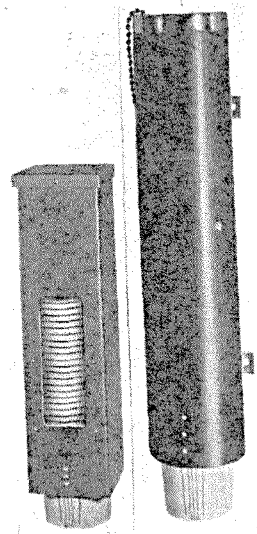

Fig. 171

The multiple duties of a stewardess and the comparatively large number of passengers make it important to give her all aids necessary to divide her attention equally among the occupants of the plane, including the flight crew. She should be provided with a suitable working space which is large enough to prepare the trays and any necessary special diets (Fig. 170). Icewater should also be obtainable without assistance of the stewardess, with well designed water and cup dispensers in convenient reach of all passengers (Fig. 171).

In trans-oceanic airliners, it is advisable to arrange for cooking facilities since long-stored food will lose its taste. Therefore, such planes have galleys completely equipped with stove, refrigerator and other utensils needed for preparation of full-course meals for as many as 85 persons. Refrigerators may be either electric or flame type. Dry ice will often suffice as refrigerating agent, if the supply can be replenished at major stops. Heat for stoves can be furnished electrically (preferably)—and by means of glycol or steam-carrying coils connected to boilers in the engine exhaust. Meals are prepared by regular chefs and served by stewards. On the Boeing Clippers operated by Pan-American the spacious lounge is converted into a regular dining room during meal time (Fig. 172). All furnishings and utensils are specially designed for lightness, utility and eye appeal.

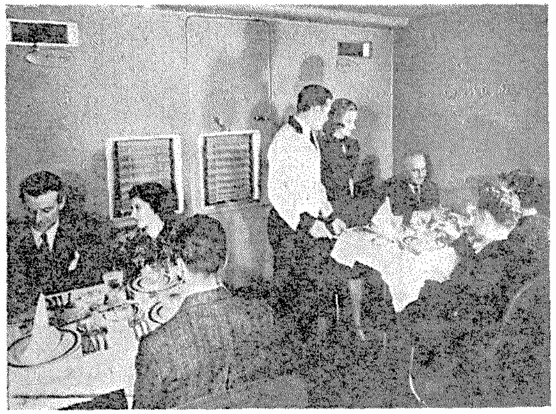

Fig. 172

2.2 LAVATORIES on military airplanes are usually limited to a toilet. However, some facilities for washing are quite useful for such personnel as the navigator or others who have to handle maps, records and charts. Means for cleaning are likewise desirable in administering first aid.

Airplane toilets are of very simple construction and consist, in most cases, only of a seat, which may be hinged, and individual bags made from watertight paper which are sealed after use and disposed of either when flying over the open sea or after landing. Figure 173 shows a patented design proposing a metal receptacle, a hinged seat and an accordion-shaped, multiple bag with numerous, individual compartments which are automatically sealed after use. The seats should be made from wood or plastic but never from metal. Toilets should be located so as to be in a comparatively warm and draftless area of the plane and properly vented or ventilated. No matter how primitive, they must be provided on all military planes of cabin and compartment-type.

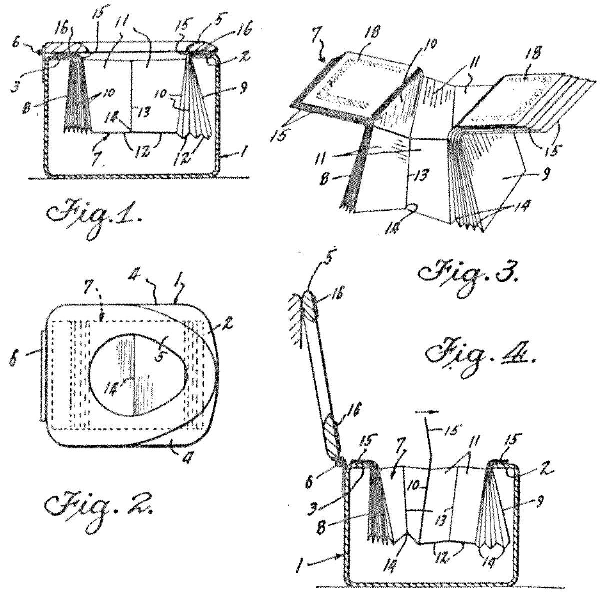

Fig. 173

Lavatories on commercial planes have to meet incomparably greater requirements. They must, of course, afford absolute privacy and, on large craft, individual rooms for women and men. They should be roomy and furnished amply and in good style. Water is essential, with hot water as an added feature.

The modern airplane traveller is spoiled and expects all of the conveniences of his home bathroom save shower. In addition, he requires freedom of motion and is very annoyed if he bumps into something every time he turns around or bends over. It is most interesting to see how well individual designers have solved these problems which are among the most puzzling of cabin design.

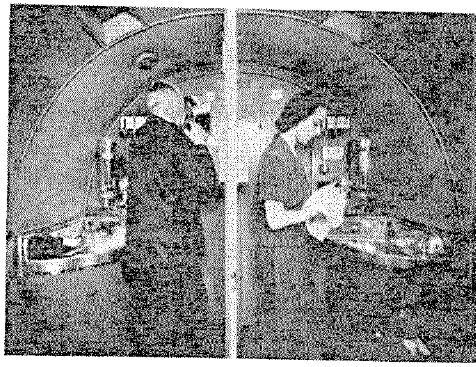

Fig. 174

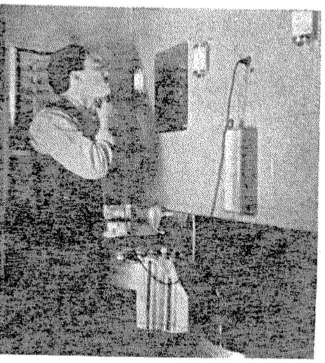

Fig. 175

Figure 174 shows the men's and women's dressing room on one of United Air Lines' pre-war sleeper planes. These rooms contain every accessory required and, despite the small space, permit their use without discomfort. Where more space can be allotted, lavatories are designed with a maximum roominess and elegance as on the Boeing 314-A Clipper (Fig. 175) and the women's dressing room aboard the Boeing 307-B Stratoliner (Fig. 176).

The wash basin seen in Fig. 176 is provided with faucets for cold and hot running water. Of course, such convenience is possible only on very large planes where the weight of a few gallons of warm water and facilities for heating or storing it do not count as heavily as on a smaller plane. Water may be heated either in a main storage tank or, if the piping to the lavatory is long enough to make weight and heat losses a consideration, in separate tanks located in or adjacent to the lavatory. Heating may be

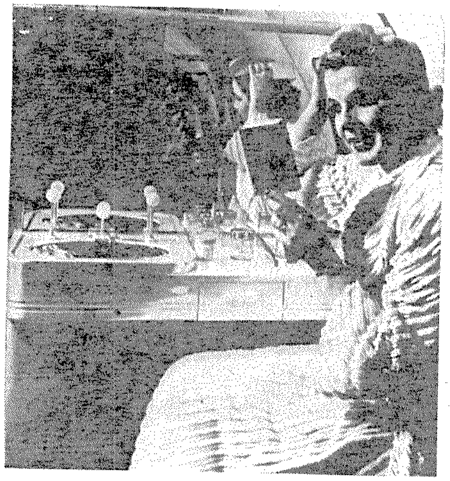

Fig. 176

accomplished by electric immersion heaters or copper coils through which steam or hot glycol is circulated. Thermostatic controls are necessary under all circumstances. A storage method is employed in the installation shown in Fig. 176. The handles seen to the left and right

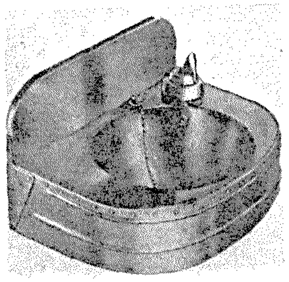
Fig. 177

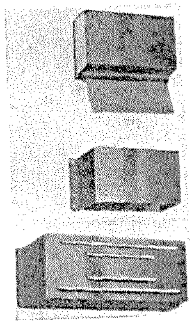
Fig. 177-A

are actually small pumps by which both the hot and cold water are sucked up from thermos containers and into the basin. This scheme has several advantages in that it discourages the waste of water and avoids need for heating. However, it is not feasible for consumption such as on very large and trans-oceanic planes.

Medium-sized passenger planes without sleeper service usually contain only one lavatory which requires much less space since facilities for dressing need not be elaborate. Wash basins furnish cold water only and are designed for compactness and convenience rather than for luxury (Fig. 177). This applies equally to other accessories such as the paper and towel holders shown in Fig. 177-A.

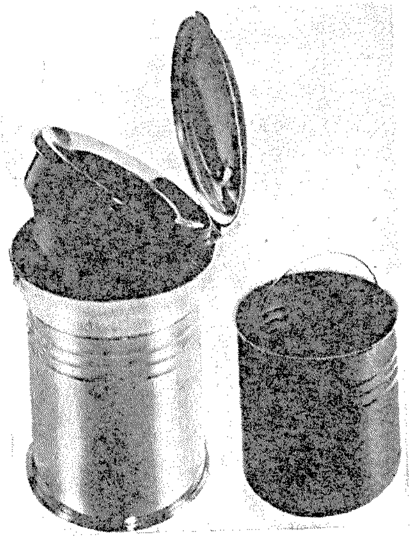
Fig. 178

The design of a suitable toilet is another difficult problem. It must be light, compact, comfortable and sturdy. Although there are systems which use waste water from the galley for flushing, most airplane toilets collect the waste in removable containers which are filled with a deodorant and germicide, and are emptied only during stop-overs. This requires means for preventing nausea of passengers by covering the contents of the receptacle and properly venting it. A toilet of this kind is illustrated in Fig. 178 which shows seat and cover, hinged to an outer container, and the inner container or receptacle.

A more elaborate model is shown in Fig. 179. It can be lifted out in its entirety or emptied by removing the top. The pipe seen at the left serves for attachment of a vent. Toilets like this are suitable for use on large airliners which may also provide urinals, stamped from lightweight metal and covered with vitreous enamel (Fig. 180).

Common requirements for all airplane lavatories are outlets for electric shavers, adequate ventilation and heating, suitable illumination, fresh-air nozzles and call buttons.

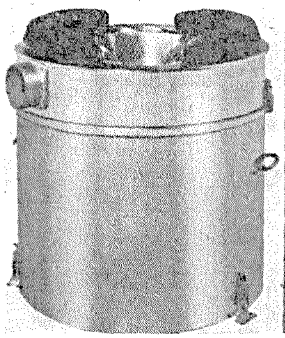
Fig. 179

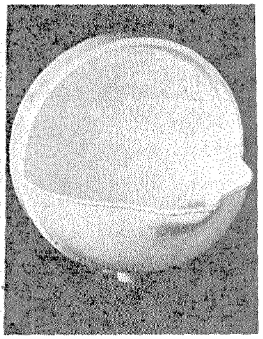
Fig. 180

2.3 EASE OF MOTION. Although not directly the responsibility of the comfortization engineer, ease of motion through the plane should be emphasized in the interior design.

The average military plane, with few exceptions, is equipped with narrow cat-walks interrupted by the high steps of bulkheads, making quick movement from one part of the plane to the other difficult and dangerous. Flooring adds weight but, apart from providing means for better motion, it will aid in the heat- and soundproofing of the plane and thus save weight for these installations. Railings along the walks are desirable, even if they are only rope. They help prevent falls and consequent injuries to crew members or damage to accessories during rapid changes of the plane's attitude.

Dressed in heavy flight gear, weighted down by oxygen equipment and often carrying bulky loads, military crews are sometimes so badly handicapped in their movements that they cannot execute their tasks as efficiently and speedily as required. Particularly during combat, rapid movement from one part of the cabin to the other, such as quick relief for wounded, may actually spell the difference between victory and defeat. To provide a reasonable ease of motion through the plane and in or out of stations, with adequate illumination of cat-walks and similar places, it is not necessary to add much weight or space to existing equipment. Consideration of the human body's physical requirements will help increase its efficiency and endurance, and thus add to the usefulness of the plane.

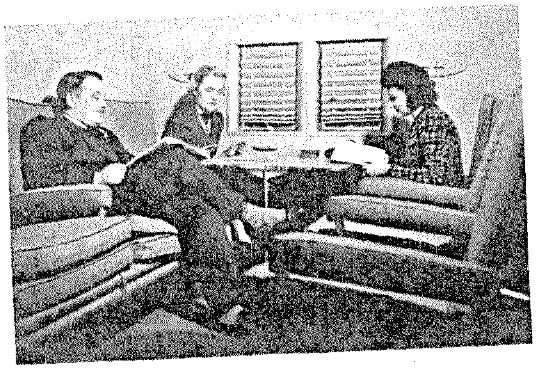

Fig. 181

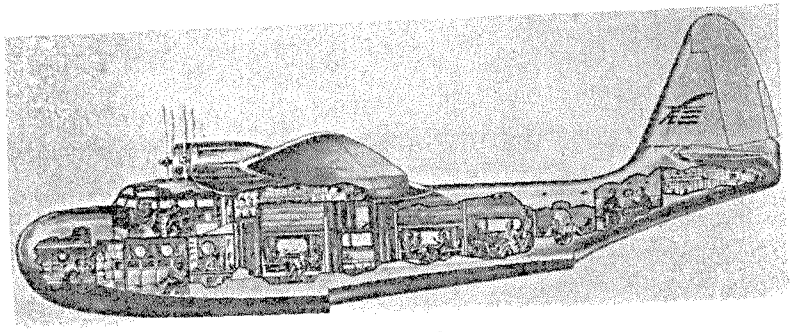

Fig. 182

In commercial airplanes, motion of passengers through the cabin may not be considered vital nor desirable. On the other hand, passengers should be able to move out of or into their seats with minimum discomfort and be able to walk comfortably to a drinking fountain, toilet or magazine rack. Figure 181 shows the arrangement of a compartment on the Boeing 314-A Clipper which is exemplary in this respect. Low allowance for space is no excuse for impeding the motion of passengers.

The "Flying Aces" of American Export Airlines, converted from a design for a Navy Bomber, were mentioned earlier. Inasmuch as such conversions will become a frequent necessity after the war, it is highly instructive to examine the cut-away view of this plane in Fig. 182, and to see how splendidly utility and passenger cabins are arranged, providing both comfort within and easy communication between individual compartments. This is emphasized even more in Fig. 183, which shows a view down the aisle as seen from the lounge of this plane.

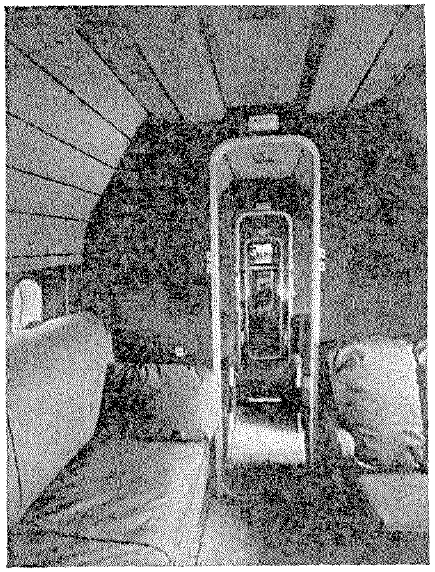

Fig. 183

3.0 COMMERCIAL COMFORT

"Comfort of Air Travel," "Styling" and "Entertainment" are not required on military planes; these therefore, are classed as commercial, compartment comfort. Their purpose is to make travel on airplanes not only comfortable but a pleasure.

3.1 COMFORT OF AIR TRAVEL refers to provisions which tend to minimize discomforts such as air sickness, ear trouble and similar effects of travel at high altitudes and at great speeds.

While military flight personnel can be selected for its suitability, airlines carry every type of passenger and must try to educate people who fear the discomforts of air travel. These discomforts are greatly reduced on modern airliners by special design and careful piloting. On the other hand, there are persons who become sick even in an automobile so that there must be limits below which a certain amount of discomfort becomes a matter of individual constitution.

Airlines attempt to counteract such inconveniences by increased personal service. Stewardesses are provided on every passenger plane and carefully trained in assisting passengers to the utmost. They are fully equipped to help mothers with babies (Fig. 184) or make sick

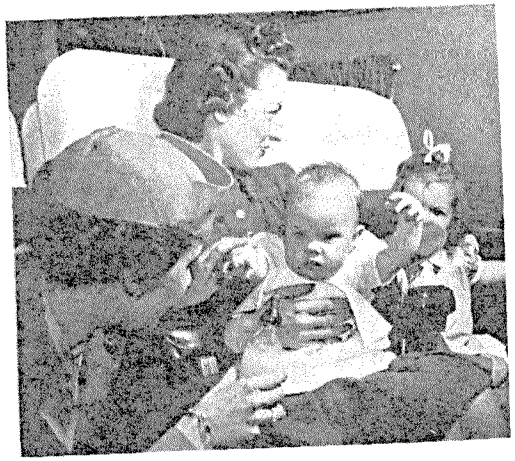

Fig. 184

persons comfortable (Fig. 185). They carry with them an assortment of implements which contain the answer to every conceivable wish of a passenger. Following are the contents of a service kit as carried by the stewardesses aboard the American Airlines' Flagships:

1	Case	Woods Emergency Type First Aid Kit (Described previously)
1	Bottle	Alka-Seltzer, 12 Tablets
1	Bag	Ammonia Inhalant, 40 per bag (in 3¾ x 6¼ Glassine)
15	Pk'ts.	Aspirin, 2 Tablets per Pk't. (in 3¾ x 6¼ Glassine)
1	Bottle	Astringosol, 1 oz.
10	Pk'ts.	Bisodol Powder (in 3¾ × 4¾ Glassine)
1	Pk't.	Chux Diaper
1	Each	Cotton Picker, Small
1	Bottle	DeGerm, full strength, 1 oz.
12	Each	Kwik Bandages (in 3¾ x 6¼ Glassine)
2	Each	Nasalators, in Original Boxes
1	Bottle	Neo-Synephrin, Bottle & Dropper, 1 oz. Original Box
1	Can	Talcum Powder, 1½ oz. Johnson's
1	Each	Atomizer, DeGerm, Empty
2	Each	Combs, Small (in one white box 3½ x 5½ x ⅜)
1	Each	Shaver, Electric, Complete
10	Books	Matches
21	Each	Airways Traffic Control Folders, T-99
2	Each	Pencils, Black Lead, No. 2
1	Each	Pencils, Red Lead
1	Deck	Playing Cards
1	Pad	In Flight Stationery
50	Each	T-11 Identification Tags

Fig. 185

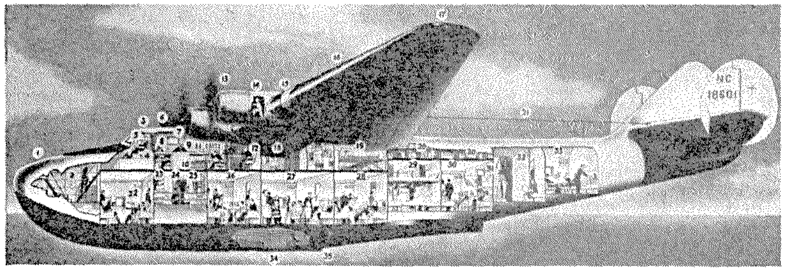

Fig. 186

Stewardess call buttons operating a visual annunciator system are provided for every passenger, as are ash trays and other conveniences, as well as sanitary containers for persons who become sick. Chewing gum is offered to counteract the effects of changes in altitude during take-off and landing.

The extent to which an airline must go to make air travel comfortable for its passengers is realized by a study of the arrangement of passenger and service compartments in the cut-away view of a Pan-American Super-Clipper (Fig. 186). Following are the stations as denoted by the numbers in the picture: (1) Anchor Hatch (2) Seaman's Compartment (3) Bridge (where the flying controls of the liner are located) (4) First Pilot (5) Second Pilot (6) Radio Direction Finder "Loop" (7) Navigation Compartment (8) Radio Officer's Post (9) Chart Room-Navigator's Post (10) Map Case, Marine Library, Drift-Sight Bombs, Flares, Navigational Instruments (11) Engineering Officer, and Mechanical Engine and Aircraft Controls (12) Captain's Office (13) 1500 hp Wright "Cyclone" engines equipped with Hamilton constant speed, automatic adjusting propellers (14) Mechanic's Wing Station (15) Controllable landing lights (16) Wing Span 152 ft (17) Navigation Lights (18) Main Cargo Hold which extends way into Wing (19) Crew Sleeping Quarters (20) Luggage Holds (21) Radio Aerial (22) First Passenger Compartment with accommodations for 10 persons (23) Spiral Staircase to Bridge (24) Men's Retiring Room (25) Galley in which two stewards can work simultaneously and where food can be prepared for 85 persons (26) Second Passenger Compartment with accommodations for 10 persons (27) Dining Lounge with accommodations for 15 passengers (28) Third Passenger Compartment with accommodations for 10 persons (29) Fourth Passenger Compartment with accommodations for 10 persons, illustrating method of making up berths for conversion of airliner into ocean sleeper (30) Fifth Passenger Compartment for 10 persons (31) Ladies' Dressing Room (32) Sixth Compartment (33) Private Cabin Suite (34) Fuel Pumps for transferring fuel from Sea-Wings to Wing Tanks (35) Auxiliary Hold.

Comfort of air travel is further enhanced by the unique atmosphere of friendly helpfulness and emphasis on service which is typical for American airlines. This atmosphere surrounds the passenger from the moment he enters the airport limousine and makes him immediately comfortable, giving him a feeling of security and self-confidence which stays with him throughout the entire trip, no matter how air travel affects him.

The airlines are also showing excellent judgment and good psychology in giving instructions to their passengers. Where instructions are necessary, such as for fastening a seat belt, no smoking during landings, closing of window shades during take-offs from and landings on restricted zones or even explanations for removing non-priority passengers, they are given in such a manner as not to antagonize even the most sensitive person.

It is such appreciation of every minute detail pertaining to personal comfort which has skyrocketed the passenger miles of airlines in the United States.

3.2 STYLING of the cabin of an airliner is a challenge to the artist because it sets such limits. The weight is limited beyond what he considers reason; he must not interfere with the soundproofing scheme or illumination. His fabrics must be light, bright, porous, flameproof and washable. Bulkheads, stringers, control cables and other obstructions are all over the place and yet, his artistic scheme must surpass anything he has ever done. As a result, men like Howard Ketcham had to

create an entirely new concept of styling to meet two conditions in particular: it must be appropriate and, it should make the passenger forget that he is travelling on an airplane. The latter condition may sound odd but is easily explained.

Appointments, furnishings and comfort accessories must be designed for the utmost saving of weight and space. This may result in a design which seems to shout at every occasion: "See, how light I am!" Fixtures may look too flimsy to have appeal. Chairs may be so over-designed as to be actually ugly. Accessories may seem to stress functional design to the point where they look more ridiculous than practical. Therefore, an experienced designer will hide the lightness and simplicity of design behind a scheme which does not remind the passenger at every turn that it is necessary to save weight, weight and weight.

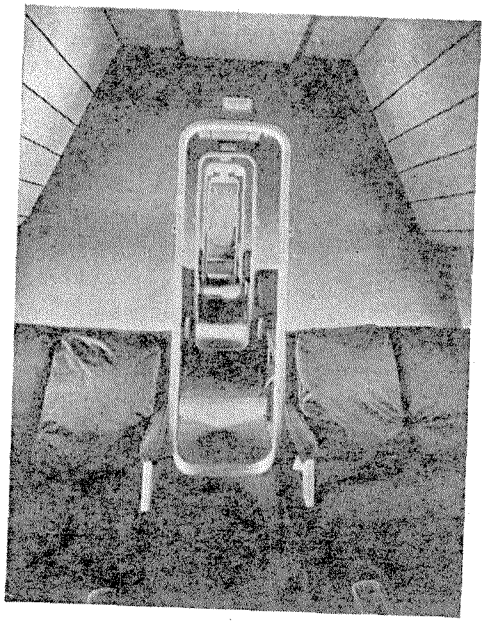

Fig. 187

Similarly, the stylist must convey the impression of roominess, even in a small cabin, and thus contribute greatly to the overall feeling of comfort. Such a design is illustrated in Fig. 187 which shows another interior view of the Flying Aces. The simple, straight lines and conservative color scheme would never remind a passenger that he occupies the cramped space between the bulkheads of what used to be a bomber.

Even greater effects can be obtained where somewhat more room is available. Most remarkable in this respect is the view of a triple compartment on a Boeing Stratoliner which was styled by Howard Ketcham (Fig. 188). Similar principles apply to every piece of accessory equipment, from elaborate chairs to simple ash receivers such as the ones shown in Fig. 189 which combine functional design with artistic appearance.

3.3 ENTERTAINMENT. As passengers become restless and tired of sitting

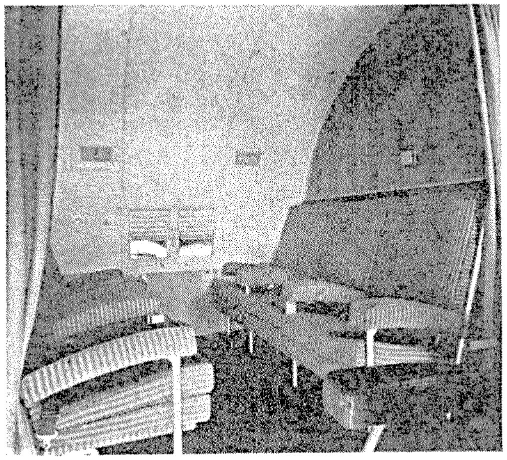

Fig. 188

Fig. 189

still, they are more likely to feel the effects of air travel, and such tedious hours on a trip may keep them from undertaking another one. For this reason, airlines provide every possible facility for entertainment or occupation of passengers. Medium-sized transports furnish magazines or writing utensils, including tables. Stewardesses endeavor to entertain children (Fig. 190) and are instructed to answer the multiple questions asked by passengers, point out interesting scenery and the like. On larger planes such as the Boeing Stratoliners, the increased spaciousness permits games of all types (Fig. 191), and nothing short of the conveniences of an exclusive club are provided in the luxurious lounge of the Pan-American Clippers (Fig. 192).

However, the main feature of entertainment on an airplane is the flight itself. The scenery below is, to most passengers, one of the foremost thrills of air travel and airlines, therefore, route their planes over interesting territory whenever possible, providing maps and descriptions of the points crossed in flight (Fig. 193).

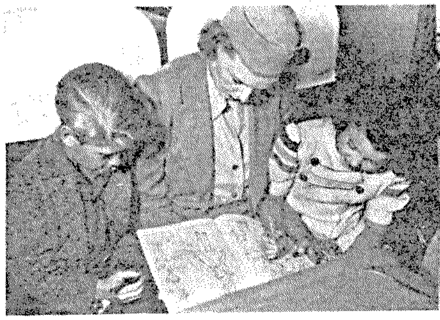

Fig. 190

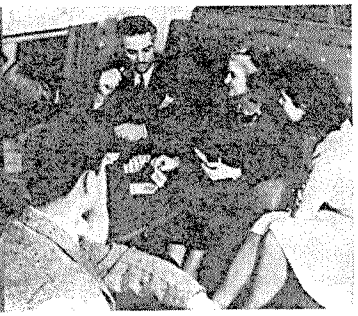

Fig. 191

Location of windows in the low-wing airplanes, presently used for continental passenger transport, are not always suitable for sight-seeing when relaxing in the chair. Further developments will undoubtedly take the desire for this comfort feature into account and provide postwar transports with arrangements giving all of the passengers a comfortable and unobstructed view of the scenery below.

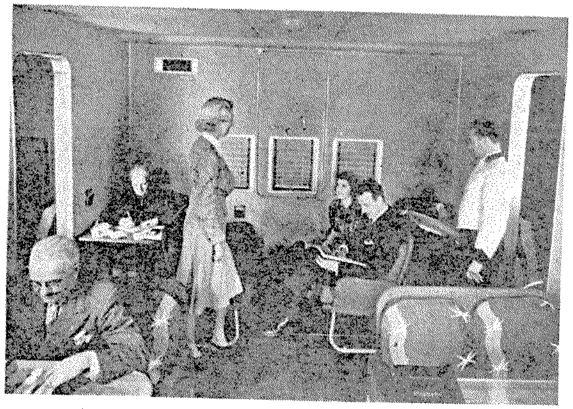

Fig. 192

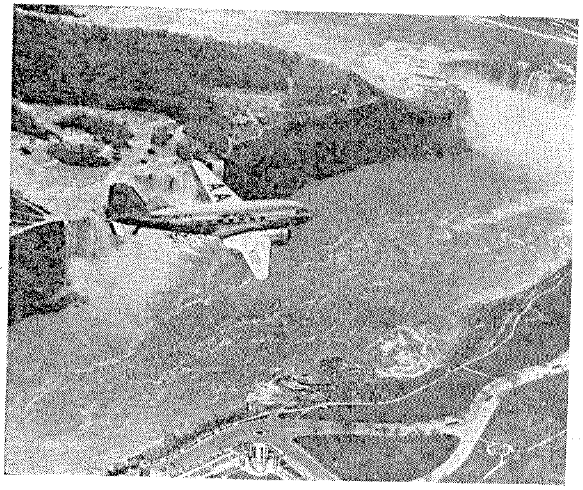

Fig. 193

4.0 CONCLUSION

This is the story of comfortization. It is by no means complete and many details have been omitted which might have been of interest. However, some of these details would have required more than the available space, others could not be told for military reasons, and others again may have been overlooked by the author because aircraft comfortization is such a vast subject.

As long as it was intended to give merely an outline of this phase of aircraft design, it was not necessary to touch on every one of its numerous problems. The concepts of comfort change with time and man. What was considered a rare luxury yesterday, is indispensable comfort today and ridiculed discomfort tomorrow. Many of the schemes and features described above may have become obsolete by the time this text reaches the reader and, in the rapidly moving stream of new developments, may have been abandoned or replaced by better, lighter and more efficient designs.

Although the ideas of what constitutes comfort may change, the physical requirements of the human body remain the same and, with them, the fundamental principles of comfortization, no matter what their practical application will be.

It is unwise for an engineer to make predictions and, in this case, foretell whether and when there will be radio and television and humidity control and other features on airliners of which today's inventors dream. There is only one fact which stands out as certain: Just as the American aircraft industry has been foremost in providing and using the tools for victory in this struggle, thus it will always be first in adopting whatever the new concepts of comfort should be in the future and, for that matter, create most of them.

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